8-2012

Sequence Stratigraphy and Depositional Systems of the Mansfield Sand, Upper Atoka Formation, Arkoma Basin, Arkansas

Scott Cherry
University of Arkansas, Fayetteville

SEQUENCE STRATIGRAPHY AND DEPOSITIONAL SYSTEMS OF THE MANSFIELD SAND, UPPER ATOKA FORMATION, ARKOMA BASIN, ARKANSAS

SEQUENCE STRATIGRAPHY AND DEPOSITIONAL SYSTEMS OF THE MANSFIELD SAND, UPPER ATOKA FORMATION, ARKOMA BASIN, ARKANSAS

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Geology

By

Scott Aubrey Cherry
Baylor University
Bachelor of Science in Geology, 2008

August 2012
University of Arkansas

This thesis is approved for recommendation
to the Graduate Council.

Thesis Director:

Doy L. Zachry, Ph. D.

Thesis Committee:

Ralph K. Davis, Ph. D.

Xiangyang Xie, Ph.D.

THESIS DUPLICATION RELEASE

I hereby authorize the University of Arkansas Libraries to duplicate this thesis when needed for research and/or scholarship.

Agreed ____

Scott A. Cherry

Refused ____

Scott A. Cherry

ABSTRACT

The Mansfield sand is an informally named member of the Pennsylvanian Atoka Formation in Arkansas. Once a productive gas reservoir, the Mansfield is situated in a double plunging anticline in the southern portion of the Arkoma Basin. The formation is internally composed of sandstone units ranging in thickness from tens of feet to over a hundred feet interbedded with shale units ranging in thickness from several tens of feet to hundreds of feet. Previous studies have focused on the stratigraphy of the lower and middle Atoka.

A detailed subsurface study of the stratigraphic framework of the Mansfield sand was conducted using conventional lithostratigraphy and sequence stratigraphy. Four progradational parasequences have been identified within a highstand systems tract. Deposition of the Mansfield occurred in a deltaic environment on a sandy, fluvial or wave dominated shoreline.

ACKNOWLEDGEMENTS

I would like to thank those who have contributed to my education and aided in the completion of my studies. First of all, to Dr. Zachry, who first introduced me to the Department and convinced me that this was the place for me. I benefitted from his humor, patience, and dedication and I am truly grateful for the opportunity to have worked with him. I would like to thank the members of my thesis committee, Dr. Ralph Davis, and Dr. Xiangyang “Cheyenne” Xie for their assistance and encouragement. I am grateful to the faculty in the Geosciences Department who truly make this a special place. Also, to my fellow students and the lasting friendships I have established during my time here.

I would like to thank my friends and colleagues in the oil patch that encouraged me to go back to school and leave behind the rigs for good. To T.H. Musgrove for his encouragement and words of wisdom. To my father, who cultivated my love of geology and not only introduced me to hiking the Ouachitas, but also the important skill of adding “Stinkum” to the wellheads of Arkoma gas wells.

To my wife, Jennifer, whose support and devotion throughout the years has been steadfast. To Juliana and Tyler, for their laughter and joy, and inspiration in the simple, daily reminders of what is most valuable.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

The Arkoma Basin is a foreland basin associated with the late Paleozoic Ouachita orogenic belt. It is situated in east central Arkansas and south central Oklahoma. The transition between passive margin and foreland basin is recorded in the strata that compose the Atoka Formation. The Atoka is a thick succession of sandstone and shale units that range in thickness from 1,000 feet up to possibly 25,000 feet (Zachry, 1983). In the frontal Ouachitas, the Atoka conformably overlies the Morrowan Johns Valley Formation, and is conformably overlain by the Desmoinesian Hartshorne Sandstone. The Atoka has been divided into three informal members, the upper, middle, and lower. The focus of this study is the stratigraphic framework of the Mansfield sand of the upper Atoka.

The Mansfield sand is an informally named sandstone unit within the upper Atoka, positioned stratigraphically above the Middle Alma and below the Upper Alma (Table 1). The regional extent of the Mansfield sand is limited geographically and is predominantly located in the areas immediately surrounding the Hartford anticline, a double plunging anticline located just southeast of Mansfield, Arkansas. The Mansfield sand derives its name from the Mansfield gas field located in the Hartford anticline which has produced economically recoverable volumes of natural gas. The first and second commercial gas wells in the state of Arkansas were drilled in 1902 in to the Mansfield.

System	Series	Formation		Sandstone Unit	Other Commonly Used Names
PENNSYLVANIAN	DESMOINESIAN	HARTSHORNE			
	ATOKAN	ATOKA	UPPER	UPPER CARPENTER	CARPENTER A
				UPPER ALMA	
				MANSFIELD	
				MIDDLE ALMA	
				LOWER ALMA	
				LOWER CARPENTER	CARPENTER B
			MIDDLE	GLASSY	
				MORRIS	SELF, TACKETT
				TACKETT	WOOLSEY, MORRIS
				ARECI	SELF
				MOYER	HOOD, UPPER BYNUM
				BYNUM	LOWER BYNUM
				FREIBURG	HENSON, PEARSON
				CASEY	HUDSON 1
				VERNON	
			LOWER	SELLS	DUNN A, McGUIRE, HUDSON 2
				UPPER JENKINS	RALPH BARTON, UPPER ALLEN, JENKINS
				LOWER JENKINS	DUNN B
				DUNN C	DAWSON, DAWSON A, ALLEN
				PAUL BARTON	DAWSON B, RUSSELL, LOWER ALLEN, LOWER DAWSON
				HAMM	CECIL SPIRO, CECIL
				PATTERSON	
				ORR	SPIRO, KELLY, BARTON, BASAL ATOKA
	MORROWAN	JOHNS VALLEY			
		JACK FORK			

Table 1. Stratigraphic column depicting the Morrowan, Atokan and Desmoinesian Series with informal names and members (modified from Zachry, 1983).

The Mansfield sand is encountered at drilling depths from 800’ to 4300’ within the study area. It is internally composed of multiple sandstone units, ranging in thickness from 20 feet to 200 feet, interbedded with shales. The total thickness of the Mansfield ranges from 325 feet to 615 feet.

STUDY AREA

The area investigated in this study is located in the south central portion of the Arkoma Basin, centered on the Mansfield gas field. It covers southeastern Sebastian and northwestern Scott Counties, as well as a small portion of southwestern Logan County, Arkansas (Figure 1). The study area includes Townships 4-5 North and Ranges 29-31 West and is in close proximity to the northern boundary of the frontal Ouachitas.

Figure 1. Location map of study area showing counties near the Mansfield Gas Field.

The Mansfield gas field lies in a flat area known as Coop Prairie surrounded by elliptical ridges composed of sandstones in the upper Atoka, in the center of the Hartford anticline (Figure 2). The primary axis of the Hartford anticline lies on an east-northeast and west-southwest trend, which passes through the town of Hartford, Arkansas. The anticline is asymmetrical, with the southern limb exhibiting greater dip than the northern limb (Figure 3). In addition, plunge along the axis is less pronounced to the west than the east (Figure 4). Strata dip away in all directions from the crest of the axis, forming a local dome which serves as a structural trap for natural gas (Collier, 1907, and Smith, 1913).

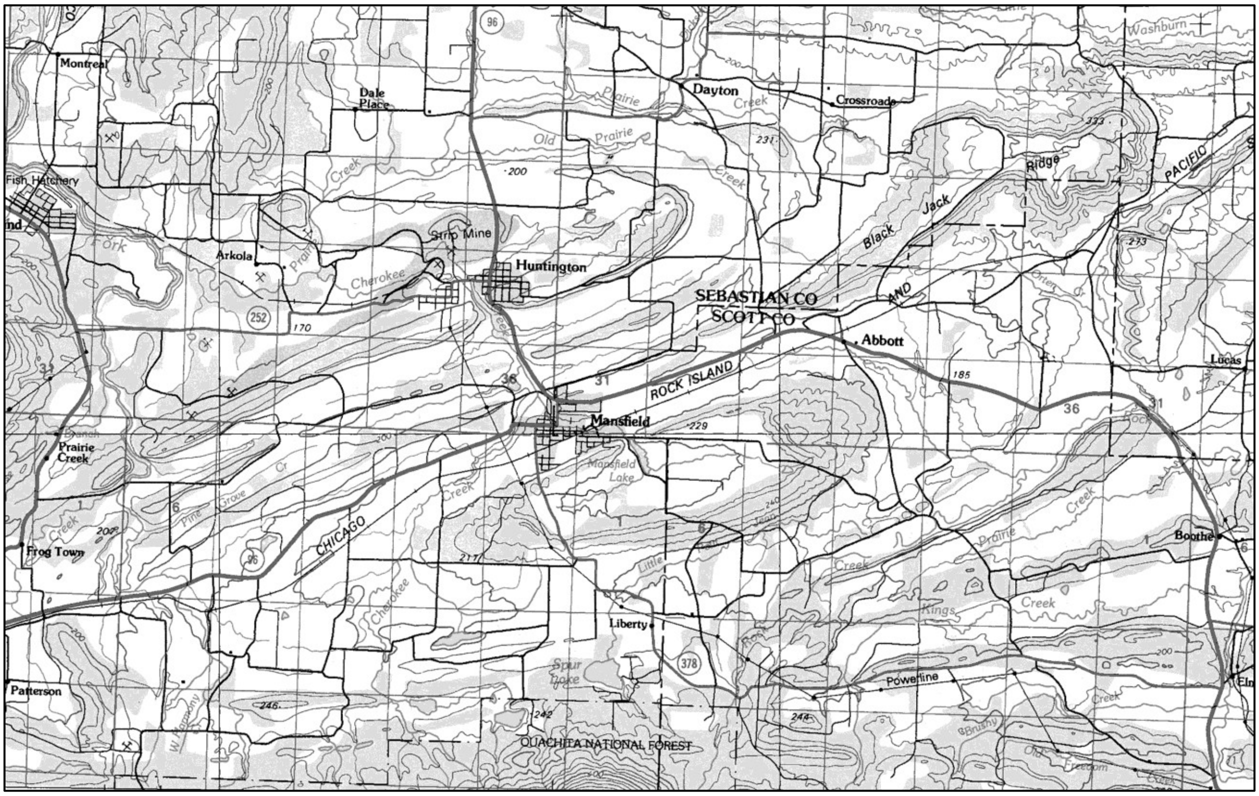


Figure 2. Topographic map of study area showing the Hartford anticline.

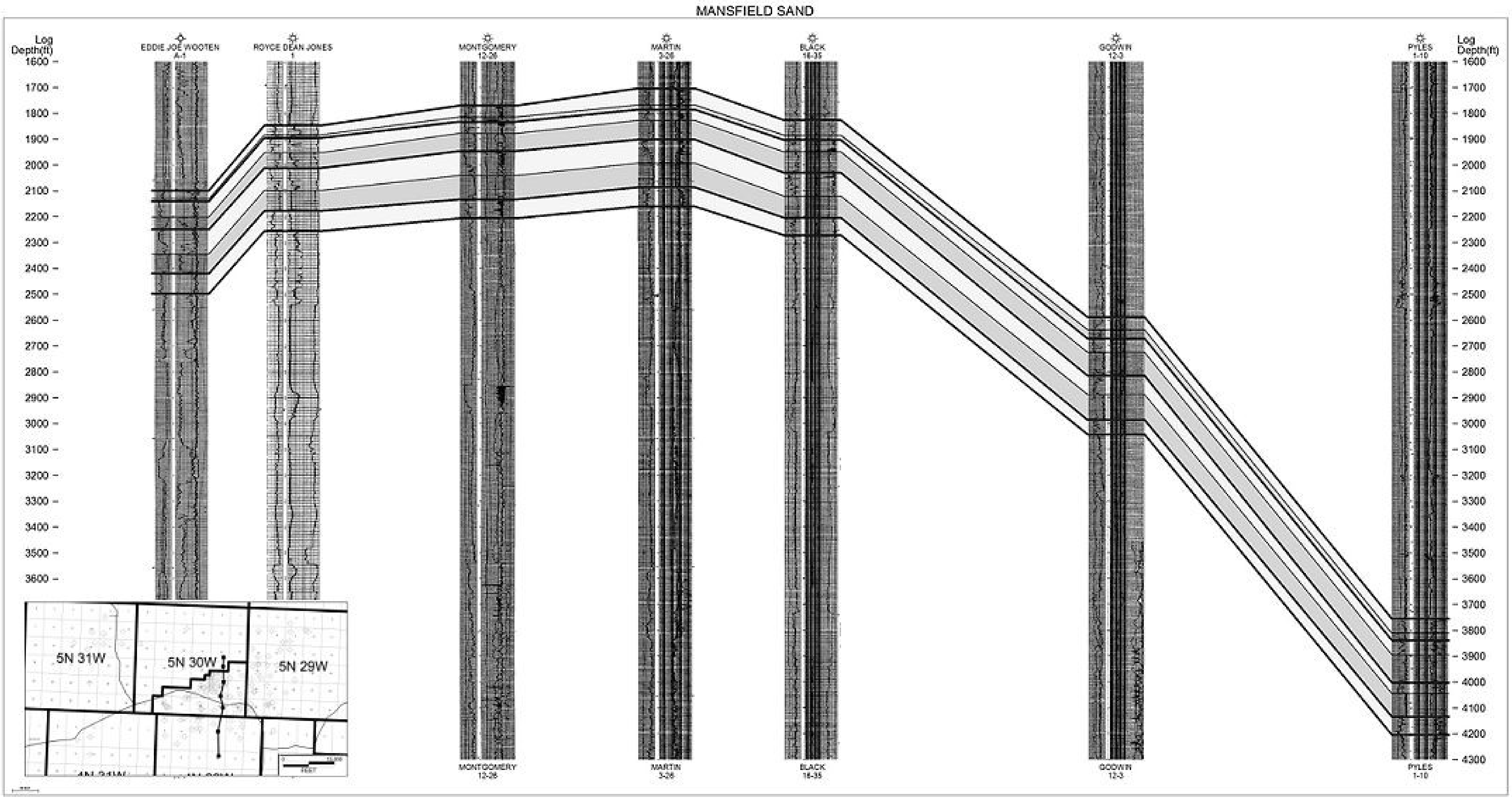


Figure 3. N-S structural cross section through the study area.

6

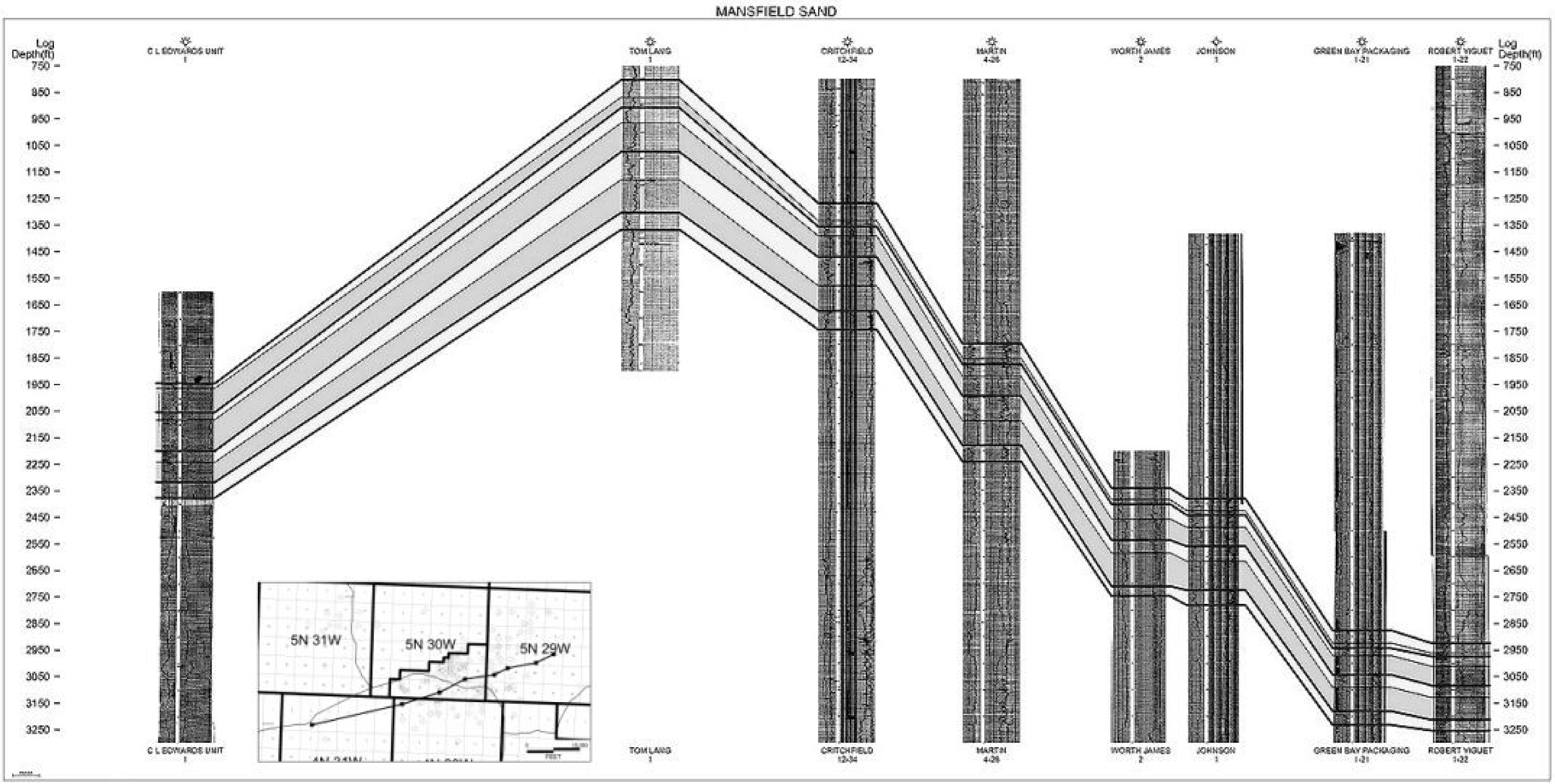


Figure 4. E-W structural cross-section through the axis of the Hartford anticline.

7

PURPOSE OF INVESTIGATION

The purpose of this study is to establish the overall stratigraphic framework of the Mansfield sand and to constrain the depositional environments. Analyses of wireline logs were used to view and interpret stratigraphic signatures and stratal patterns, with an emphasis on facies distribution and grain size changes. Delineation of genetic depositional units were used to establish parasequence architecture and infer fundamental stratigraphic controls such as sediment supply and relative sea-level change. Characterization of this interval will contribute to the current geologic understanding of the stratigraphic controls and depositional environment of the upper Atoka.

CONCEPTS OF SEQUENCE STRATIGRAPHY

Stratal patterns and stratigraphic signatures observed in the rock record are the result of the interactions of tectonics, eustasy, and climate. These factors control accommodation, the amount of sediment supply, and the manner in which accommodation is filled. Tectonic subsidence is the key control on the development of a sedimentary basin. In a foreland basin model, accommodation is created as a result of flexural loading of the lithosphere by thrust sheets. Subsidence, accommodation, eustasy and relative sea level are all linked through sequence stratigraphy. The following discussion is abstracted from Emery and Myers (1996), unless otherwise noted.

Sequence stratigraphy refers to the study of genetically related facies within a framework of chronostratigraphic surfaces (Van Wagoner, 1990). A sedimentary basin is subdivided into packages that are bound by unconformities and their correlative surfaces according to a hierarchy of scale. A sequence is a relatively conformable succession of genetically related strata bounded at its top and base by unconformities or their correlative conformities (Mitchum et al., 1977). A sequence thus represents a complete cycle of deposition.

Sequence boundaries are significant erosional unconformities and their correlative conformities that define sequences. A fall in sea level causes subaerial exposure of a previous sequence. Type 1 sequence boundaries are characterized by stream rejuvenation and fluvial incision and abrupt basinward facies shift as sedimentation bypasses the shelf as relative sea level falls forcing a shift in shoreline position. Less common are type 2 sequence boundaries in which marine areas are not subject to subaerial exposure and relative fall in sea level does not force a shift in the position of the shoreline; the term is out of favor with some, including Exxon, which considers the surface to represent a parasequence set boundary.

A sequence is made up of parasequences and parasequence sets. A parasequence is a relatively conformable succession of genetically related beds or bedsets that are bounded by marine-flooding surfaces and their correlative surfaces. A parasequence set is a succession of genetically related parasequences that form a distinctive stacking pattern bounded by major flooding surfaces and their correlative surfaces (Van Wagoner et al., 1990). The stacking patterns observed in vertical succession of parasequences make up depositional geometries that form during characteristic phases of relative sea level change.

Progradational geometries form when sediment supply is greater than the rate of accommodation creation, resulting in facies patterns that migrate basinward (Figure 5). Aggradational geometries are formed from vertical stacking patterns when sediment supply and accommodation rates are roughly balanced. Retrogradational geometries are formed by stacking patterns of facies migrating landward when sediment supply is less than the rate accommodation creation. These stacking patterns and geometries formed by vertical successions of parasequences are often able to be observed in wireline logs.

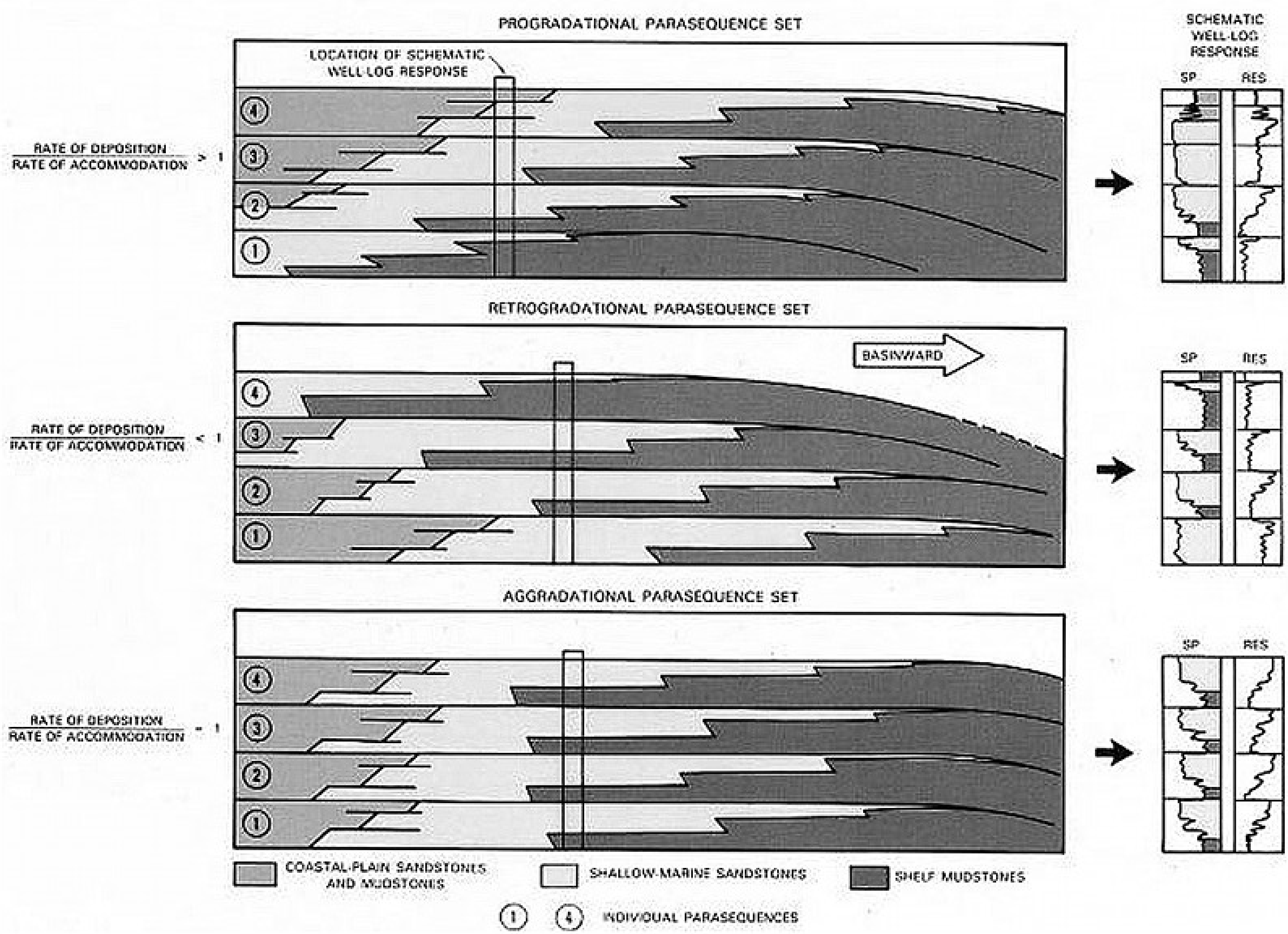


Figure 5. Parasequence stacking patterns and associated well log signatures (from Van Wagoner et al., 1990).

The depositional geometries observed in parasequence sets typically form in predictable distinct packages to form systems tracts. A systems tract is a three dimensional assemblage of lithofacies defined by internal geometry and the nature of its boundaries (Emery and Myers, 1996). The basal systems tract in a depositional sequence that represents the oldest stratigraphically is the lowstand systems tract (LST). Deposited during an interval of relative fall in sea level and subsequent sea level rise, accommodation volume is overtaken by sedimentation supply, yielding a transition from progradational to aggradational parasequence sets. The transgressive systems tract (TST) follows as sediments onlap the underlying LST as accommodation volume increases at a rate faster than sediment supply. When the shoreline reaches its most landward position, maximum transgression is marked by a depositional surface known as the maximum flooding surface (MFS), which marks the upper boundary of the TST. Following the TST, sediment supply exceeds the rate of accommodation and relative sea level rise during the highstand systems tract (HST), marked by a transition in parasequence sets from aggradation to progradation.

Important to establishing chronostratigraphic framework through sequence stratigraphy is hierarchy of scale (Figure 6). A cycle of relative or eustatic change of sea-level that has duration on the order of 100 to 200 million years is known as a first order cycle (Mitchum, 1977, AAPG Memoir 26). A second order cycle, or supercycle, is a cycle of relative or eustatic sea level change that has duration on the order of 10-100 million years. A third order cycle, or depositional sequence, occurs on the order of 1-10 million years. This sequence contains no internal unconformities and is made up of systems tracts and their parasequences. Cycles of the fourth order make up parasequence sets and high frequency fifth order cycles make up individual parasequences. The fourth and fifth order cycles occur on a scale of tens of thousands to hundreds of thousands of years, and are typically observable at the outcrop, well log, or seismic section scale.

Tectono-Eustatic/ Eustatic Cycle Order	*Sequence Straigraphic Unit*	Duraction (my)	*Relative Sea Level Amplitude (m)*	*Relative Sea Level Rise/Fall Rate (cm/1,000 yr)*
First		>100		<1
Second	Supersequence	10-100	50-100	1-3
Third	Depositional Sequence Composite Sequence	1-10	50-100	1-10
Fourth	High Energy Sequence, Parasequence and Cycle Set	0.1-1	1-150	40-500
Fifth	Parasequence, High-Frequency Cycle	0.01-0.1	1-150	60-700

Figure 6. Cycle hierarchies in sequence stratigraphy (from Mitchum et al, 1977).

REGIONAL SETTING

Three major physiographic provinces dominate the geology of western Arkansas. The Ozark uplift in northern Arkansas and southern Missouri serves as a major boundary that influences areas to the south. The Arkoma basin, which includes the study area, is a significant source of natural gas. The Ouachita fold and thrust belt to the south was during orogenesis a driving force in development of the Arkoma basin.

THE OZARK UPLIFT

The Ozark uplift is a broad, asymmetrical uplift with the apex located in southeastern Missouri (Figure 7). Precambrian igneous rocks are exposed at the core in the St. Francis Mountains. Extending into northern portions of Arkansas and northeastern Oklahoma, Paleozoic strata dip gently away from the center of the complex to form a concentric pattern of successively younger strata to the southwest. The dome is divided into three broad plateau surfaces of increasing elevation: the Salem Plateau, the Springfield Plateau, and the Boston Mountains Plateau. The Salem Plateau is underlain by Lower Ordovician dolomites and limestones, the Springfield Plateau is capped by Lower Mississippian limestones and cherts, and the Boston Mountains are capped by alternating sandstones and shales of the Pennsylvanian Atoka.

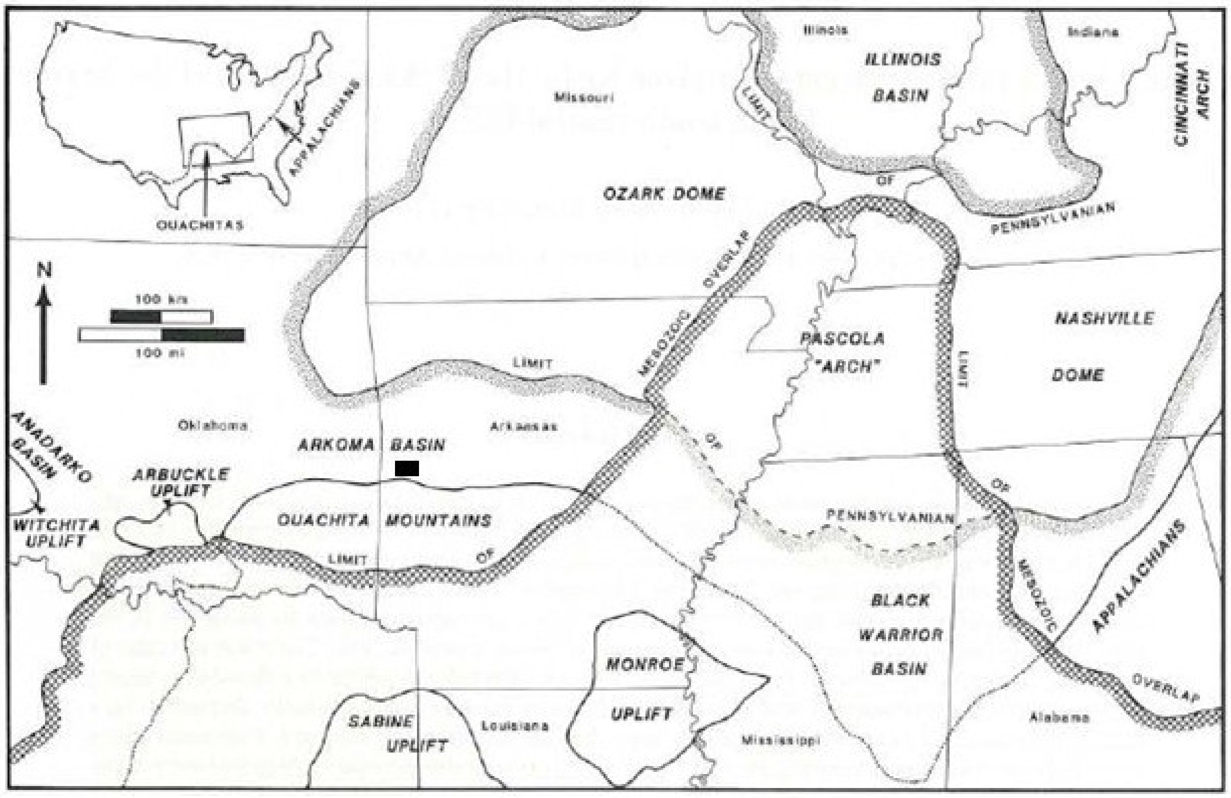


Figure 7. Map showing study area in relationship to local geologic provinces (modified from Houseknecht, 1986).

A sub-province related to the Ozark uplift has been identified as the North Arkansas Structural Platform (Moyer, 1985). The area is characterized by complex structural systems composed of monoclines and normal faults that trend east-west. The area represents a transitional boundary between the Ozark uplift and the Arkoma basin that developed on a stable cratonic shelf that has undergone slight structural deformation. Pre-Atokan carbonates, shales and sandstones are the dominant lithology. Slight regional dip to the south is prevalent, increasing gradually into the adjoining Arkoma basin.

ARKOMA BASIN

The Arkoma basin is a peripheral foreland basin extending 250 miles from the Mississippi River Embayment in east-central Arkansas to the Arbuckle Mountains in south-central Oklahoma along an arcuate trend (Houseknecht, 1986). Ranging in width from 20 to 50 miles, the basin is bounded in Arkansas on the north by the Ozark uplift and by the Ouachita fold and thrust belt to the south (Zachry and Sutherland, 1983). Sedimentary fill in the basin is asymmetric with 1,000 feet of accumulation in the north and estimated 25,000 feet in the south. Thick units of dark gray to black fissile shale are interbedded with lenticular fine-grained sandstones. These deposits accumulated on a marine shelf with an influx of clastic sediments from the north and northeast. Flexural loading from thrust sheets associated with the Ouachita orogeny caused development of down to the south growth faults, dramatically increasing accommodation volume in southern portions of the basin.

OUACHITA FOLD AND THRUST BELT

The Ouachita fold and thrust belt is a complexly folded and faulted megastructure that extends approximately 1,300 miles from west Texas to east-central Mississippi. The largest surface exposure of this megastructure appears in west-central Arkansas, known as the Ouachita orogeny. The Ouachita orogeny trends east-west across eastern Oklahoma and western Arkansas approximately 100 miles and marks the southern boundary of the Arkoma basin. Highly deformed Paleozoic strata have been thrust over the southern margin of the North American craton in numerous imbricate thrust sheets. Ordovician to lower Mississippian deep marine strata are overlain by Mississippian to Pennsylvanian flysch deposits.

TECTONICS

Within the past few decades, a single theory has emerged to gain widespread acceptance as to the mechanisms that formed the Arkoma basin. During the late Precambrian or early Paleozoic, a major rifting event resulted in the creation of an ocean basin south of North America. The coastal zone became a passive margin along the southern edge of North America (Figure 8). Sedimentation accumulated along the Atlantic type passive margin in shelf and off-the-shelf environments, creating a wedge of slope, rise, and abyssal sediments. During the Devonian or early Mississippian, the ocean basin began to close as subduction began beneath a converging plate known as Llanoria. As convergence continued, an accretionary wedge associated with subduction caused the Ouachita orogeny.

Sedimentation rates were relatively slow throughout the Mississippian in the shelf along the southern margin, dominated by shallow marine and non-marine environments. The deep ocean basin was marked by rapid deposition of thick flysch. Sediment was dispersed longitudinally westward across the basin accumulating in submarine fans, forming the Stanley, Jackfork and Johns Valley formations in abyssal settings.

By the early Atokan time, the ocean had been consumed by subduction and accompanying convergence of Llanoria. Flexural loading by thrust sheets on the North American plate resulted in bending along the southern margin, and ultimately the development of normal faults downthrown to the south. As the shelf slope was destroyed by the northward migration of syndepositional faulting, subsidence and sedimentation rates increased substantially, resulting in abrupt thickness increases of Atokan strata across the faults. Rapid deposition of terrigenous clastics from the east occurred during the Middle Atokan. The stair step pattern formed by the

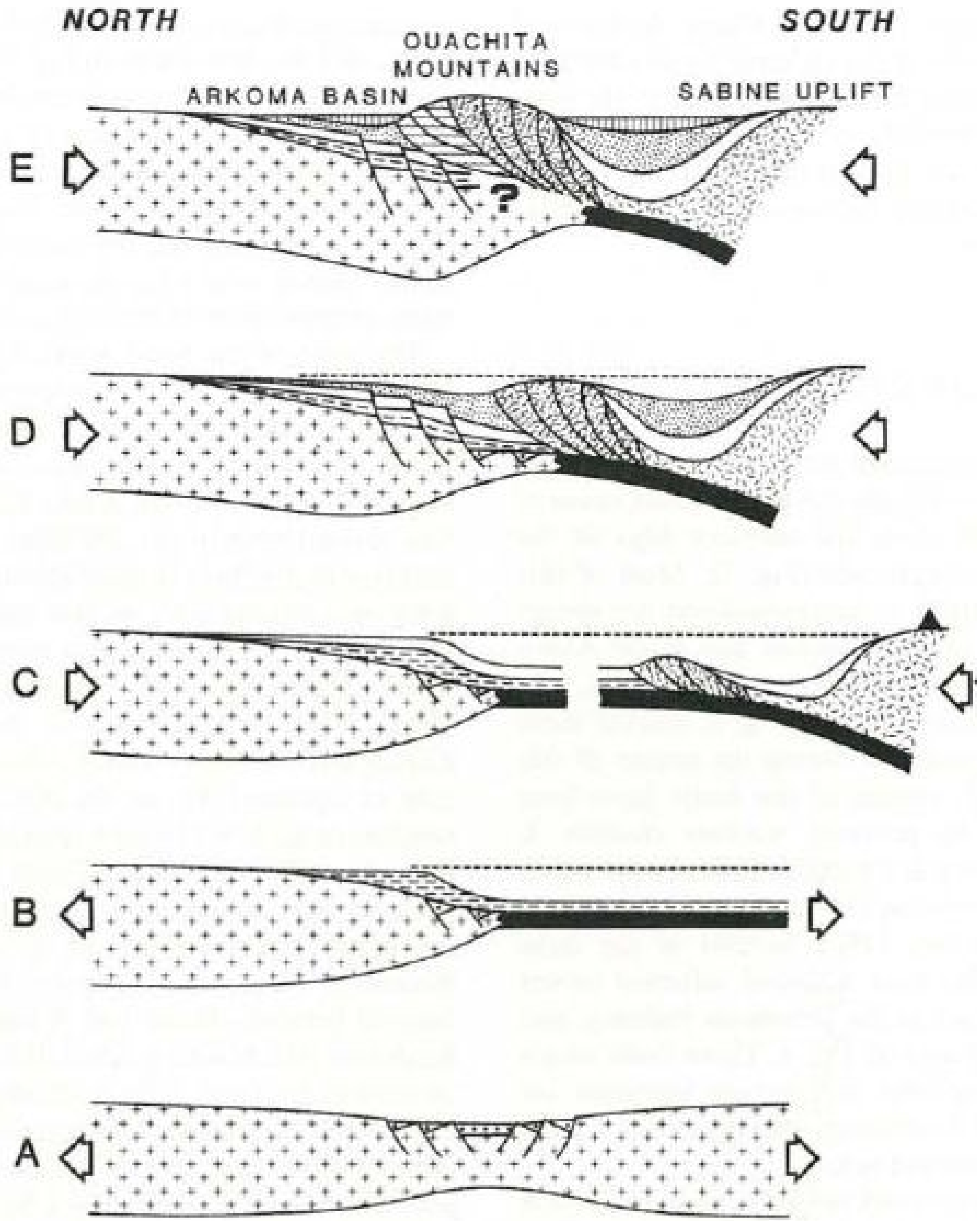


Figure 8. Cross section illustrating tectonic development of the Arkoma basin and Ouachita orogeny. (A) late Precambrian - early Paleozoic, (B) late Cambrian - early Mississippian, (C) early Mississippian - early Atokan, (D) early - middle Atokan, (E) late Atokan – Desmoinesian (from Houseknecht, 1986).

development of growth faults fundamentally controlled the distribution and thickness of Atokan deposits within the Arkoma basin (Figure 9). Uplift of the Ouachita fold and thrust belt during the late Atokan time marked the end of convergence and completion of the Arkoma basin as a peripheral foreland basin. Deposition in the Arkoma basin continued in shallow marine, deltaic, and fluvial environments. By the Desmoinesian, no thickness increases to the south across faults occurred and the structural configuration was complete, appearing essentially the same as present day.

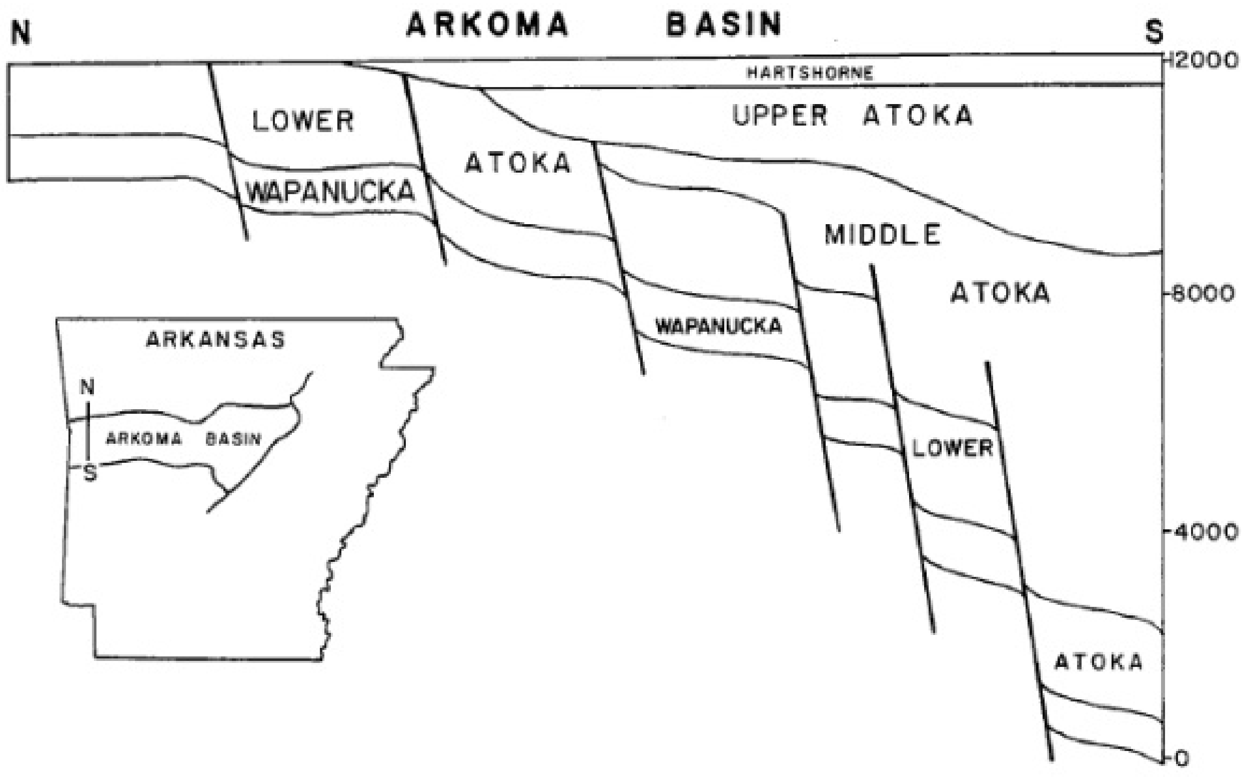


Figure 9. North-south section across the Arkoma Basin showing informal members of the Atoka Formation (Zachry and Sutherland, 1984).

STRATIGRAPHY OF THE ATOKA

The Atoka Formation was formally named by Taff and Adams who first described an outcrop of shale and siltstone interbedded with sandstone near the town of Atoka, Atoka County, Oklahoma (1900). At that time, the lithological description was vague and no type section was designated. Despite the presence of regular drilling activity, efforts by operators focused strictly on production, and detailed investigations into facies distribution and depositional environments were not undertaken. Numerous investigations over the last several decades have dramatically increased the current understanding of the depositional systems that formed the complex successions of shale, siltstone, and sandstone. Many individual sand bodies have been the focus of unpublished studies and masters theses in various locations within the basin, both in subsurface investigations as well as outcrops.

LITHOSTRATIGRAPHY

The Atoka Formation has the largest areal extent of any Paleozoic unit in Arkansas, with surface exposures in the Boston Mountains, Arkansas River Valley, and the frontal Ouachitas. In the Arkansas River Valley and Frontal Ouachitas, the Atoka has been subdivided into lower, middle, and upper lithic members based on regionally mappable intervals. The formation is a thick sequence of marine, mostly tan to gray silty sandstones and grayish-black shales, with some rare calcareous beds and siliceous shales, which may reach up to 25,000 feet thick in the Ouachita Mountains (McFarland, 2004). The harder intervals dominated by sandstones form ridges and prominent topographic features where they crop out. Sandstone members are irregularly bedded, lenticular bodies with variable lateral continuity, subject to thinning, stacking, and pinch out. The Atoka is conformable with the Johns Valley Shale in the Ouachita Mountains, and is conformably overlain by the Hartshorne Sandstone.

Atokan strata were deposited in shallowing upward environments in a deep ocean basin, on the slope and shelf. The base of the Atoka contains deepwater turbidites that ultimately transition to fluvial-deltaic sediments of the middle and upper Atoka. Rapid rates of deposition occurred during a period of rising sea level and decreasing precipitation along the axis of the rapidly subsiding foreland basin, with sand bodies generally oriented east-west (Figure 10)(Coleman, 2000).

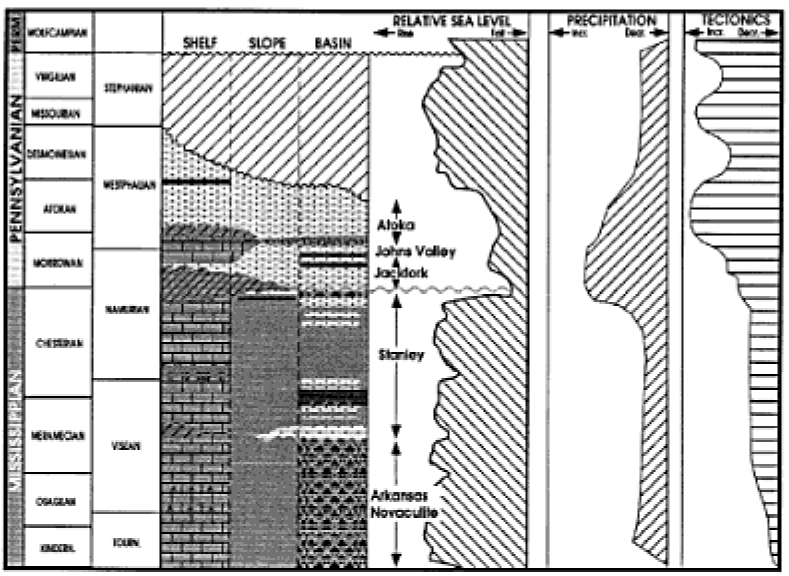


Figure 10. General lithostratigraphy with relative sea level, precipitation and tectonic of the Arkoma basin (Coleman, 2000).

While subdivision into the three informal members has widely become accepted, only two members of the Atoka have been formally named, both at the base of the formation, the Trace Creek Member and Greenland Sandstone Member. Both are exposed in northwest Arkansas. An informal nomenclature has emerged, however, as a result of drilling for natural gas. The units are named for the various production fields within the Arkoma basin (Zachry,1983). Table 1 presents the nomenclature adopted by the exploration and production industry to identify productive sandstone intervals within the Atoka in a stratigraphic context.

SEQUENCE STRATIGRAPHY

Previous investigations of the Atoka suggest that the entire succession, along with the overlying Hartshorne Sandstone, represents one third order cycle (Valek, 1999). The basal Atoka overlies a type 1 sequence boundary, marked by subaerial erosion and stream rejuvenation. The lower Atoka marks initiation of the lowstand system tract in which a relative rise in sea level caused northward migration of the shoreline, followed by the transgressive system tract. The middle Atoka contains several aggradational sandstone-shale alternations, and a shale unit above an interval identified as the Areci sand marks the maximum flooding surface for the sequence. The highstand system tract continues into the upper Atoka and overlying Hartshorne Sandstone.

The Atoka Formation represents a single third order composite sequence without any internal unconformities and made up of distinct LST, TST, and HST. Estimations for the duration of deposition range from 3-4 million years (Manger and Sutherland, 1990) to 5 milllion years (Houseknecht, 1986). The alternations of sandstone and shale within the Atoka are fourth, and possibly fifth, order cycles attributed to local climatic conditions influencing sediment supply and relative sea level fluctuations, while thick, continuous shale intervals are the result of tectonic activity during foreland basin development (Woolsey, 2007).

METHODOLOGY

From the study area, 331 wells were selected based on log quality and appropriate drilling depths (Figure 11). Several wells drilled in the study area were drilled to total depth within the productive gas zone and failed to penetrate the base of the formation. Modern drilling techniques, most notably directional drilling, have resulted in a resurgence of drilling activity in the study area, primarily in the dry gas reservoirs at the base of the lower Atoka. As a result, many logs have become available that capture the Mansfield sand interval and allow a more detailed delineation of the areal and stratigraphic distribution of the formation. The highest concentration of available data is in the vicinity of the Mansfield gas field. Wells to the west are shallow coal-bed methane wells that fail to penetrate the formation top. Many of the wells on the northern margin of the study area targeted the basal Atoka sands and only zones of interest below the Mansfield were logged.

Utilizing IHS PETRA® software, wireline logs obtained from IHS databases were used to create a database for the study area. Depth calibrated smartRASTER files processed by A2D Technologies were available for much of the study area. Raster images that required manual depth calibration were also incorporated to increase the resolution of well data. Formation tops and bases were entered into the database, and isopach values were calculated for wells within the study area. Gamma ray and resistivity markers were the primary indicators used to generate lithologic correlations for the top and base of the formation.

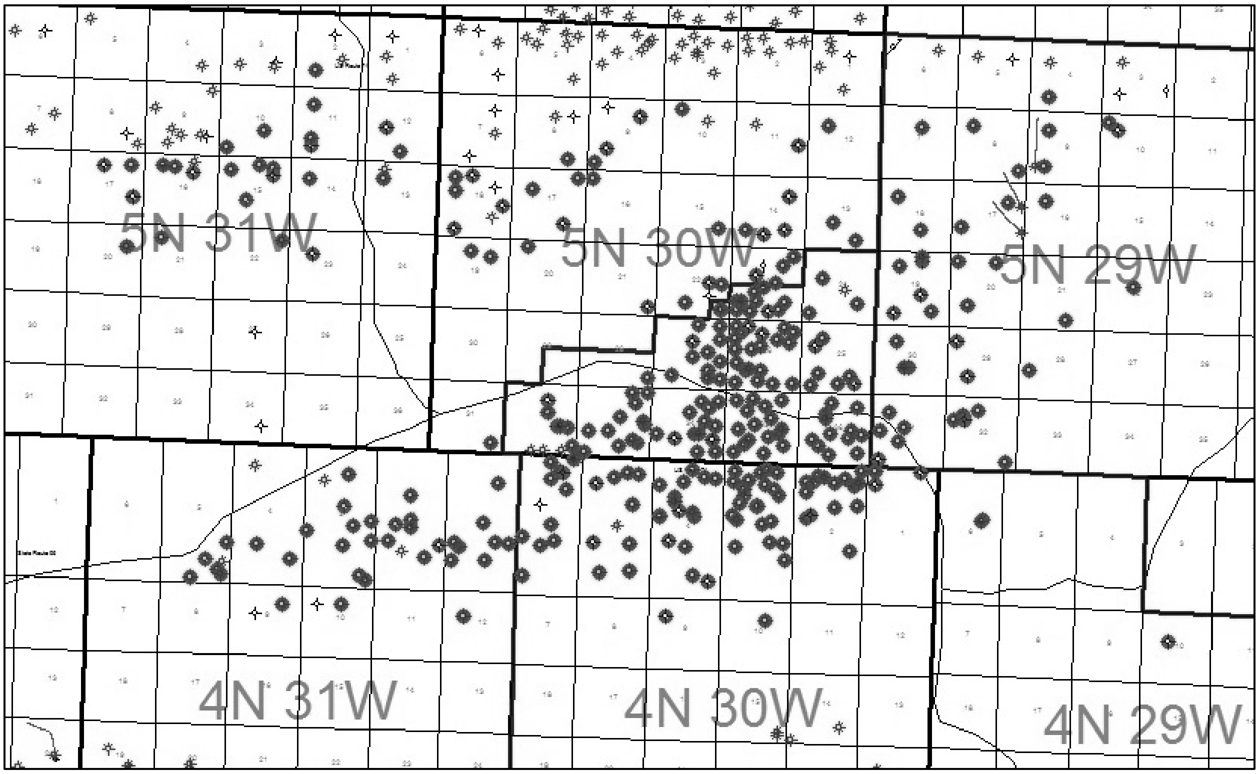


Figure 11. Location of wells within the study area.

Gamma ray logs record the natural radioactivity in formations from naturally occurring uranium, thorium, and potassium. These elemental sources are commonly found in clay minerals that make up shales, thus GR logs serve as an important tool for identifying lithology, as well as facies and sequences, and key stratigraphic surfaces used for correlation. High gamma ray values most frequently indicate shale, while sandstones show low gamma ray values, as quartz, the principal component shows no radioactivity (Rider & Kennedy, 2011).

Resistivity logs measure formation response to electric current. The higher the resistivity, the more difficult it is to conduct electrical current. While the principal use of resistivity logs is to detect potential hydrocarbons, they may also be used to a degree to resolve lithology. Resistivity is intrinsically related to rock texture and porosity. Gross characteristics of resistivity tend to be constant in a restricted zone and therefore useful in lithology distinction. In sand-shale sequences, characteristics of shale may be constant and sands may be similar and with constant fluid salinities. While direct identification of lithology from resistivity logs alone is not necessarily possible, subtle lithological changes are evident and can be used to infer facies changes (Rider and Kennedy, 2011).

Interpreted formation intervals were further divided into discrete small-scale units based on key stratigraphic surfaces, identified by log markers and related to stratal patterns. Once major trends were identified on logs, parasequence boundaries were defined on the basis of interpreted marine flooding surfaces and their correlative surfaces. Once parasequences were identified, the assemblages were evaluated to identify trends in parasequence thickness to infer variations in rate of sea-level rise. Stratal relationships were defined based on petrophysical properties rather than interpretation of position with respect to the sea level curve (Galloway, 1989).

MANSFIELD STRATIGRAPHY

Lithostratigraphic correlations were based on wireline logs obtained for wells within the study area. A full suite of logs was not available for every well; however gamma and resistivity, the primary logs on which correlations were based, were typically available. The Mansfield sand has a characteristic gamma profile within the study area, having distinct clean sandstone intervals at the base and top of the formation and consistent gamma markers from interbedded shales (Figure 12).

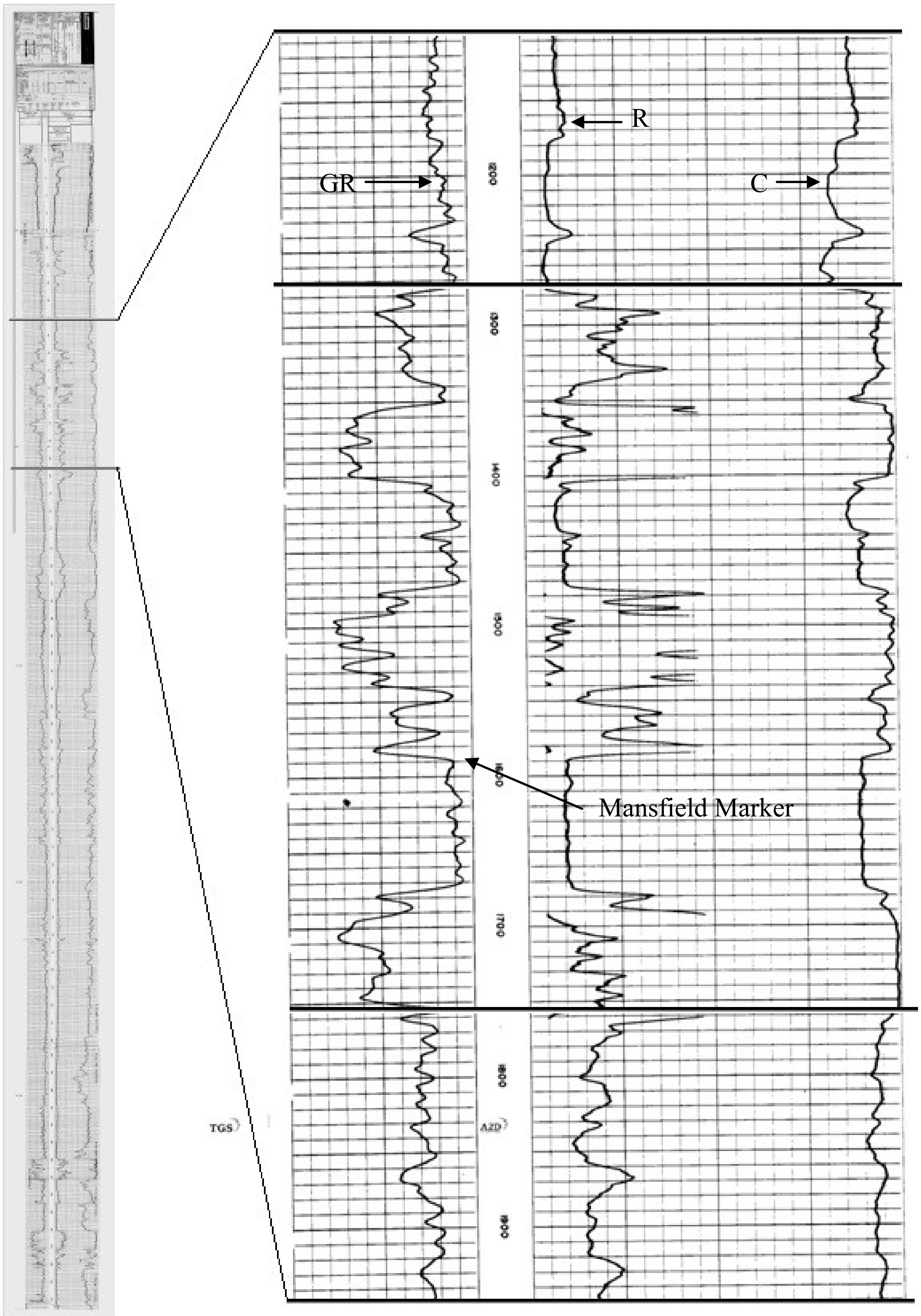


Figure 12. Mansfield sand well type log of gamma ray (GR), resistivity shallow focus (R), and conductivity (C) logged from Critchfield Unit #1.

LITHOSTRATIGRAPHY OF THE MANSFIELD SAND

The Mansfield sand can be subdivided into seven units of alternating sandstones and shales (Figure 13). The lowest stratigraphic bed in the Mansfield is an interval of sandstone (Unit A) that varies from twenty to eighty feet in thickness. Gamma signature is serrated with a blocky to bow shaped motif and has a sharp contrast from the underlying shale. Wells to the far south and west exhibit a slightly more subtle transition from shale to sand. The overlying unit is a shale interval (Unit B) varying in thickness from 75 to 180 feet. The transition from the underlying sand is typically abrupt, with most logs showing a sharp contrast in both gamma and resistivity. Gamma counts remain constant throughout the interval with minimal variation in API values. The top of Unit B appears on logs as a distinct shoulder that has been labeled by the production industry as the "Mansfield marker" and serves as significant correlative feature (Figure 12). The next interval (Unit C) is a sandstone varying in thickness from 50 to 180 feet. Gamma log generally follows a serrated funnel motif for the coarsening upward unit. The base of the unit contains fluctuations in gamma values as thin silty laminae are interbedded with thin sands. The next unit is a shale interval (Unit D) that varies from 40 to 100 feet in thickness. High gamma values are consistent throughout the unit with little fluctuation in API values. A sandstone (Unit E) varying in thickness from 25 to 75 feet follows the shale with an abrupt transition to low gamma values. The sandstone unit is clean with low gamma values, and typically appears as a funnel to cylinder motif on gamma. In northern portions of the study area, shale intercalation appears as a narrow spike in gamma value in the sandstone, but due to limited lateral continuity and vertical accumulation, has not been differentiated into a separate unit. The next unit is a shale interval (Unit F) varying in thickness from 10 to 60 feet. Lateral continuity is variable and may be inferred to pinch out at north of the study area. The final interval is a sandstone (Unit G) that varies in thickness from 20 to 145 feet. Log response for unit G is variable from cylinder or boxcar to serrated bell. Stratigraphic cross sections appear in Appendix I.

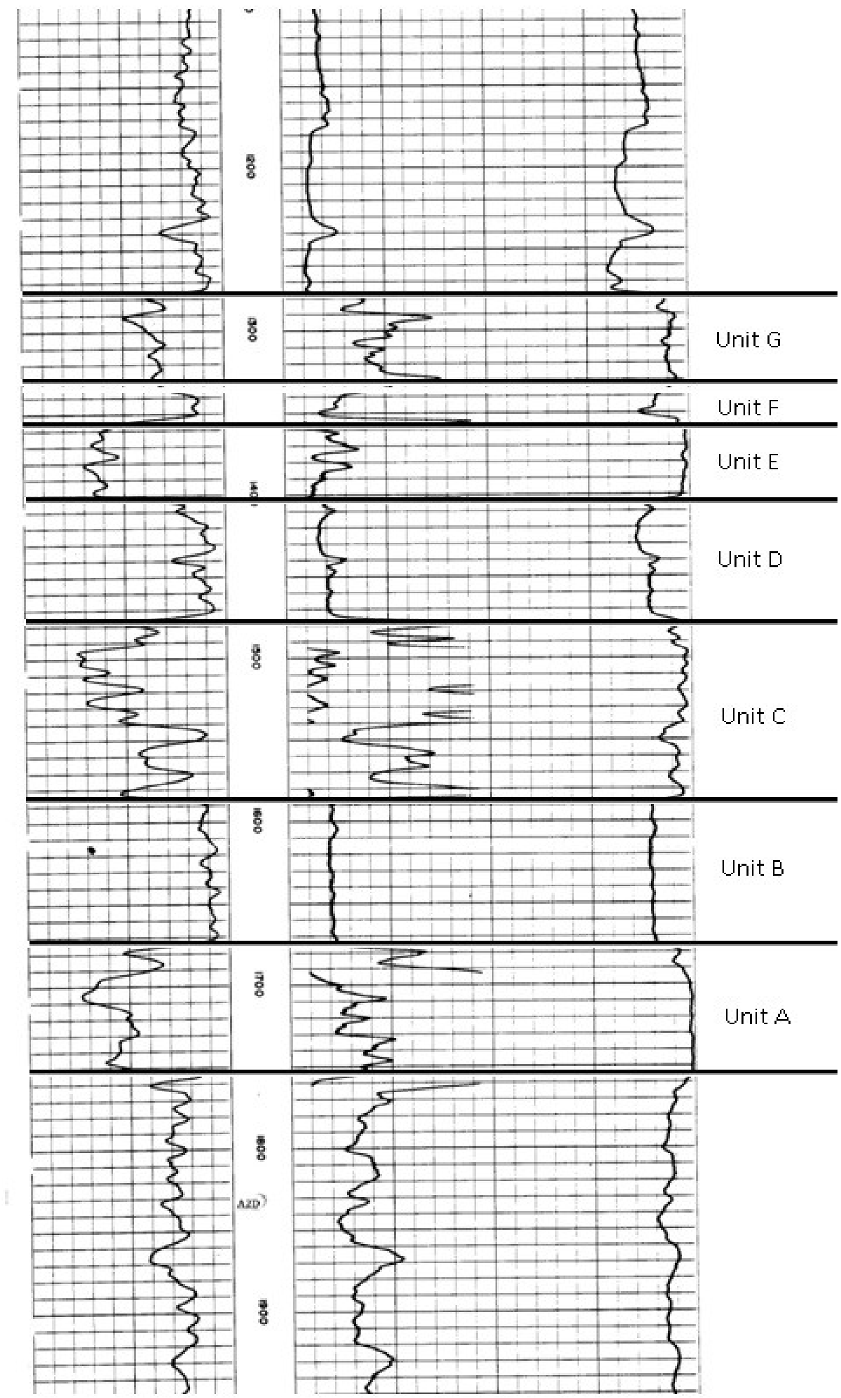


Figure 13. Lithostratigraphic divisions of the Mansfield sand. Induction log with Gamma ray in track one and resistivity and conductivity in track two.

SEQUENCE STRATIGRAPHY OF THE MANSFIELD SAND

The Atoka Formation and overlying Hartshorne represent one third order depositional sequence (Wenger, 2002). Within the Atoka, lowstand, transgressive, and high stand systems tracts have each been identified. The Areci has been used to identify the maximum flooding surface, and marks the beginning of the highstand systems tract. The Mansfield sand represents a fourth order sequence composed of fifth order parasequences in the highstand systems tract.

The Mansfield sand is subdivided into four parasequences (Figure 14). Parasequence 1 (PS1) is composed solely of Unit A sandstone. It is the first distinct packet that appears in the Mansfield sand, and overlies a thick interval of shale that is several hundred feet thick. The sandstone present in PS1 marks a dramatic shift in depositional environment from deeper marine to shallower waters. PS1 is thickest in the northern portion of the study area. An isopach map shows the areal distribution and thickness for PS1 (Figure 15).

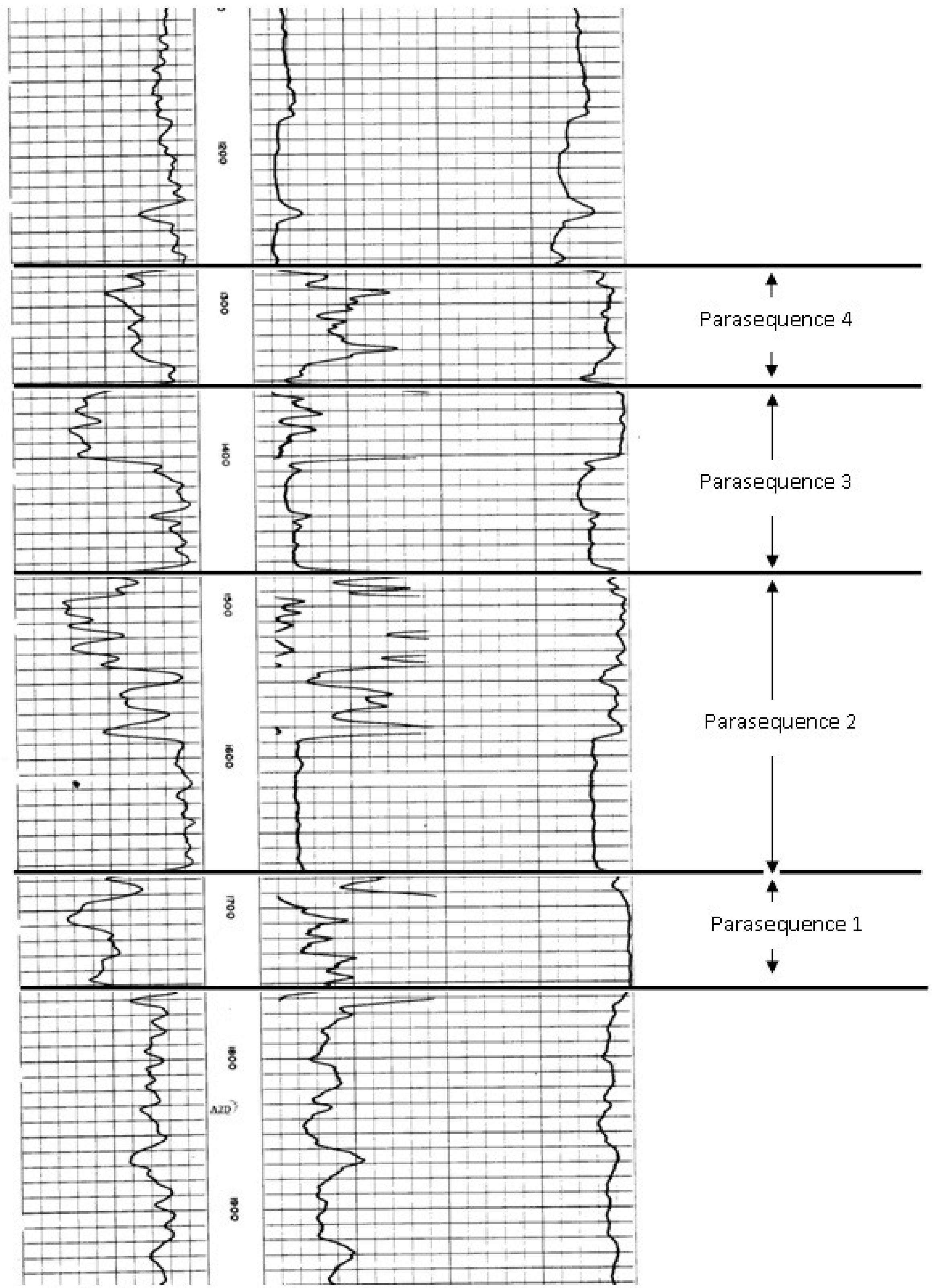


Figure 14. Parasequences of the Mansfield sand. Induction log with gamma ray in track one and resistivity and conductivity in track two.

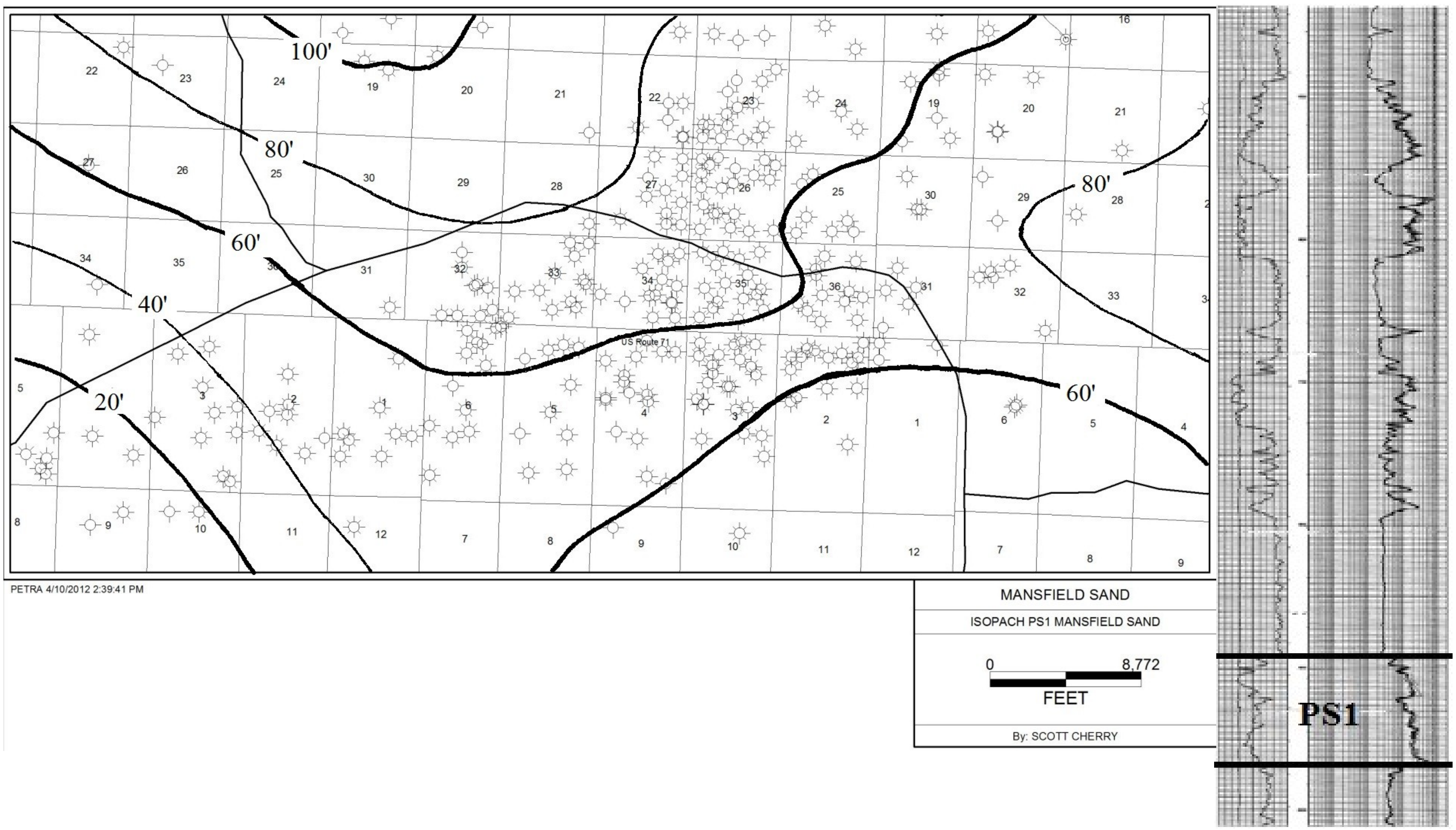


Figure 15. Isopach map of parasequence 1 of Mansfield sand.

Parasequence 2 (PS2) is composed of coupled intervals of shale and sand, Units B and C, respectively. The base of Unit B is a marine flooding surface marking a period of local sea level rise. An isopach for parasequence 2 reveals overall thickness increases westward along inferred direction of sediment transport (Figure 16). Parasequence 3 (PS3) is a couplet of shale and sand comprised of Unit D and Unit E (Figure 17). Overall thickness of PS3 is considerably less than PS2. Ratio of sand to shale volumes for PS3 appears to increase from PS2. Parasequence 4 (PS4), the final parasequence in the Mansfield sand, is a couplet of shale and sand consisting of Unit F and Unit G (Figure 18). The trend of decreasing overall thickness of the parasequence continues with PS4 being the least thick parasequence in the formation. Relative shale volume with respect to sand volume is significantly less than those observed in PS2 and PS3.

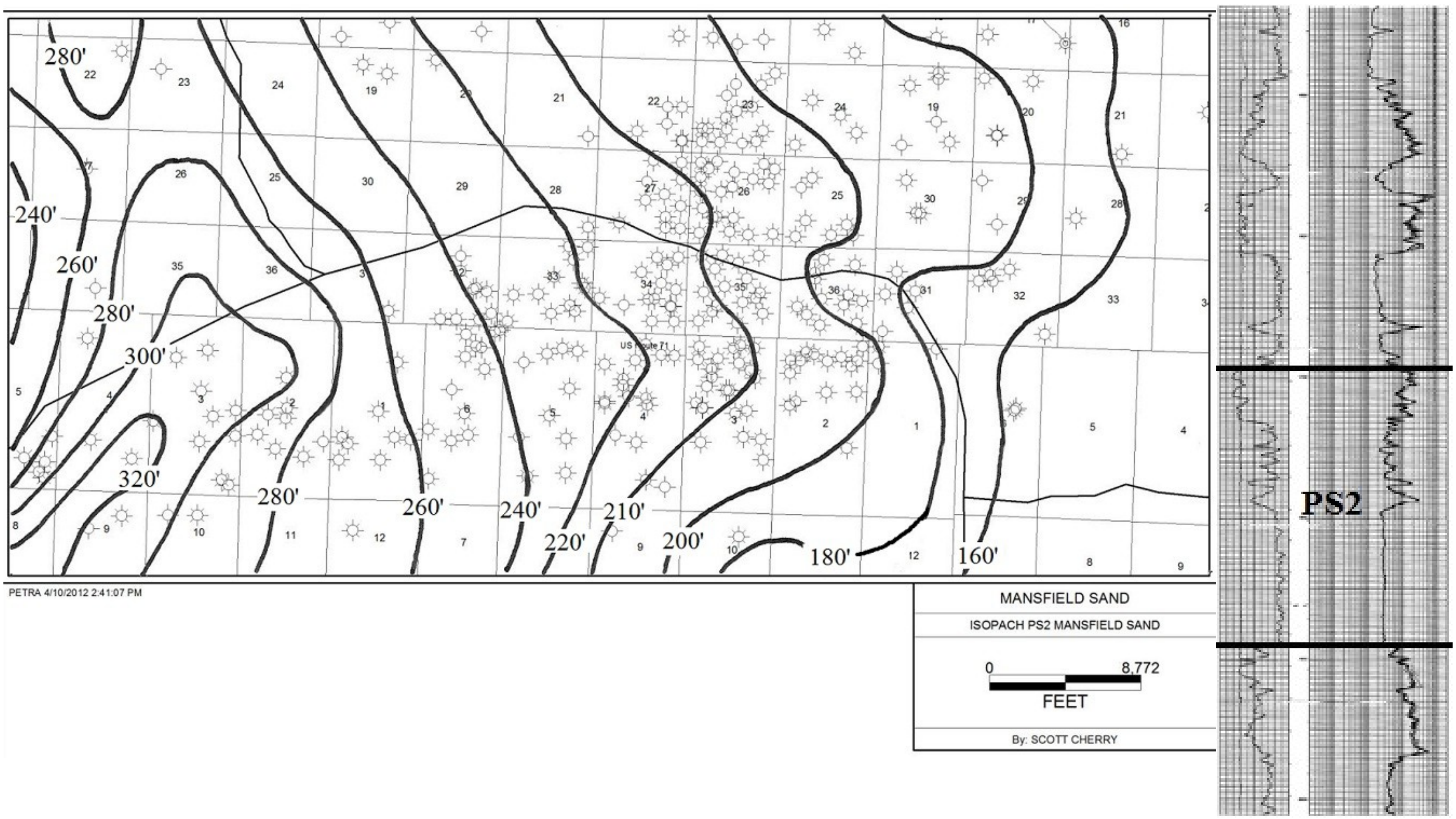


Figure 16. Isopach map of parasequence 2 of Mansfield sand.

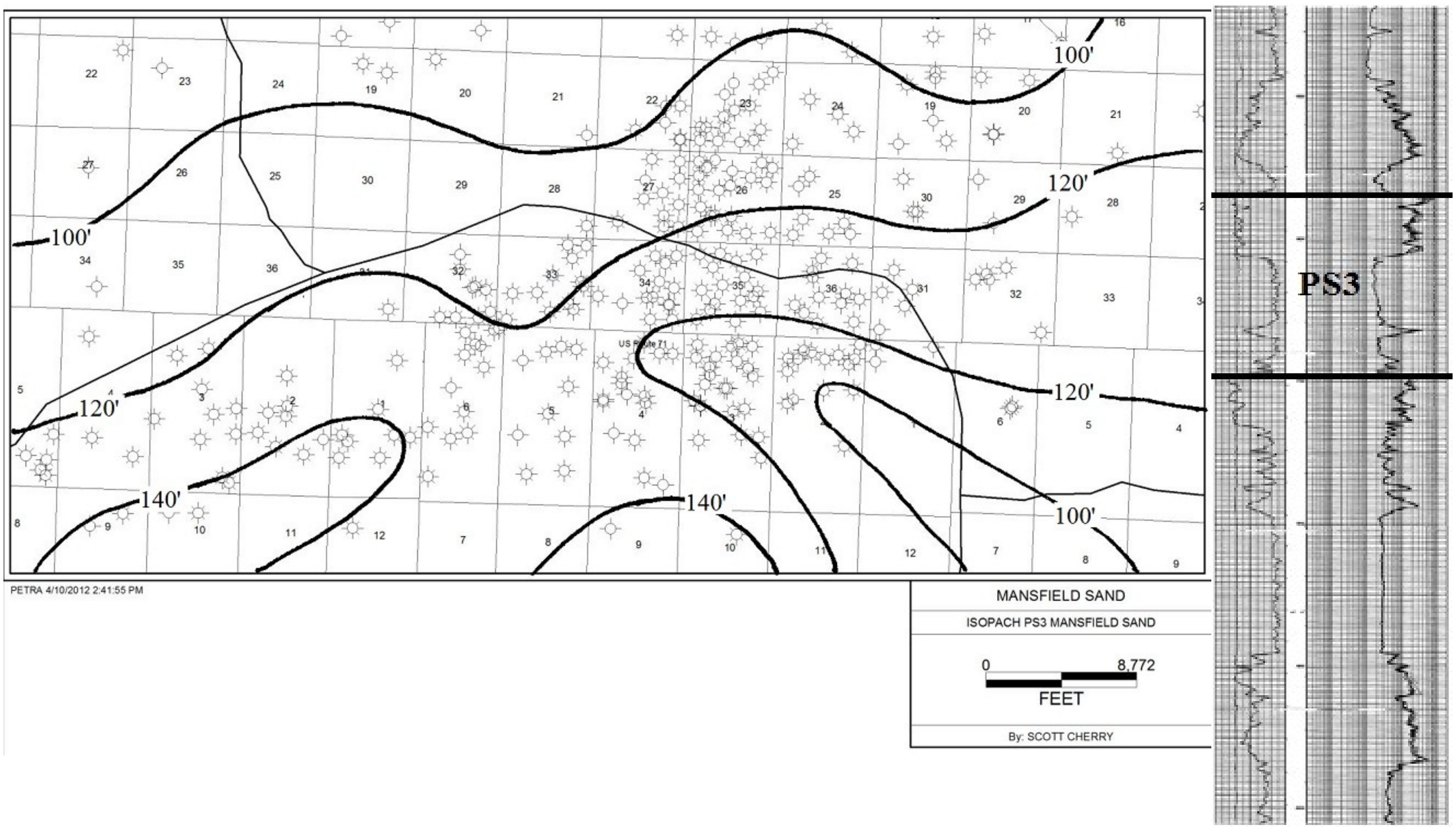


Figure 17. Isopach map of parasequence 3 of Mansfield sand.

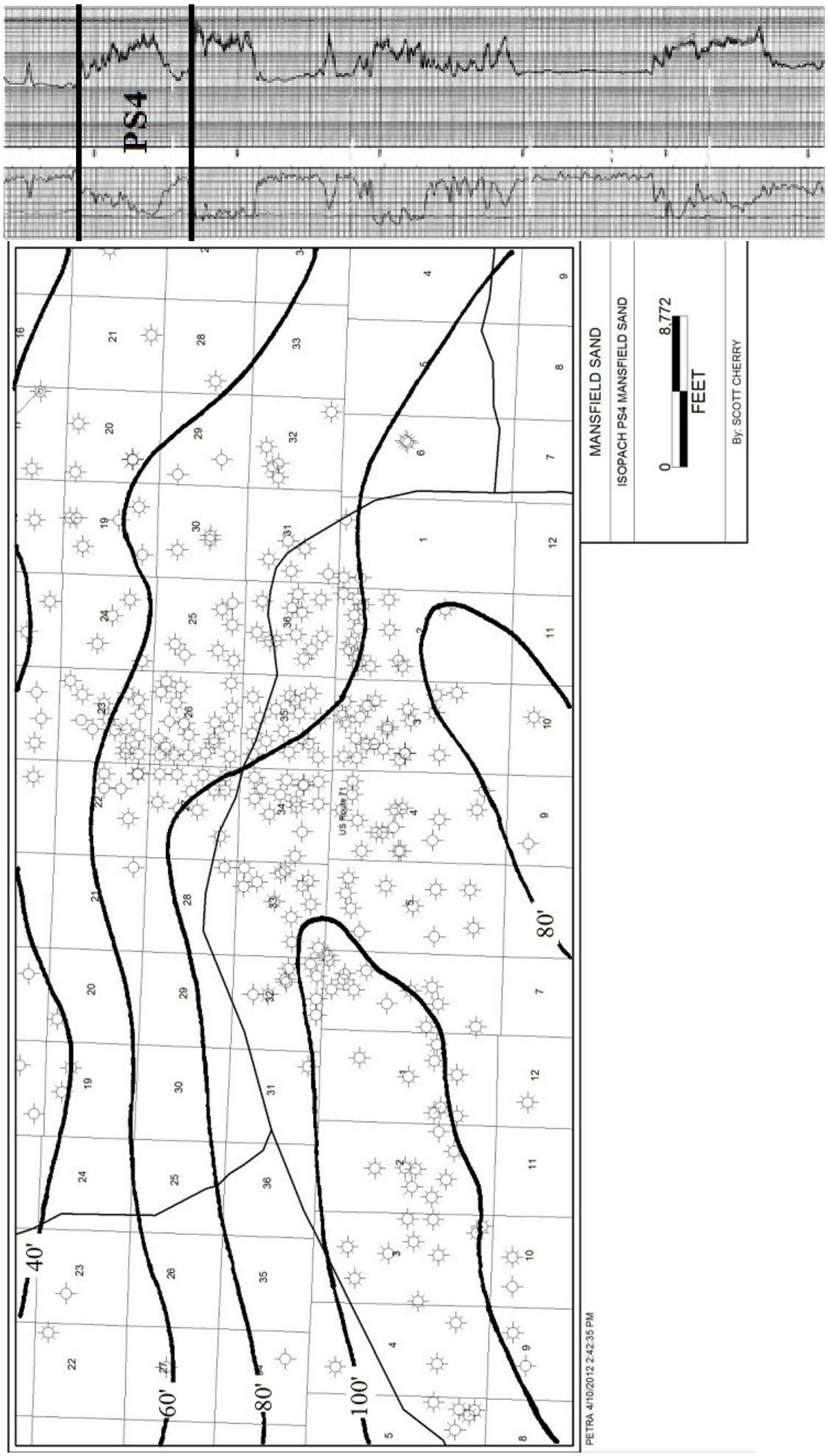


Figure 18. Isopach map of parasequence 4 of Mansfield sand.

Each parasequence is capped by a flooding surface, marking a relative rise in local sea level. Flooding surfaces have been identified by a shift in facies from clean sandstones to marine shales. Vertical stacking of these facies is consistent throughout the study area and delineation of each parasequence is based on gamma response. Each parasequence is marked by an upward decrease in gamma values, indicating an upward increase in sand to shale ratio within the parasequence. In general, sandstone bed thickness with respect to shale thickness increases upwards. The vertical stacking pattern of the Mansfield parasequences is consistent with a progradational parasequence set (Figure 5).

The primary control on parasequence thickness is the depth of the water in which the shoreline progrades. Parasequence thickness since abandonment of a previous parasequence represents rise in relative sea level. Thick parasequences result from a rapid rate of relative sea level rise, while thin parasequences result from a slow rate of rise (Emery and Myers, 1996). The trend in parasequence thickness for the Mansfield, most evident from PS2, PS3, and PS4, is that of progressively thinning parasequences. Based on this trend, deposition of the Mansfield occurred during a period of slow relative sea level rise. Episodic fluctuations related to local climatic conditions led to deposition of individual beds within the Mansfield.

DEPOSITIONAL SYSTEM

All units of the Mansfield sand possess a lobate to elongate geometry. Overall thickness increases from east to west with thinning to the north and south (Figure 19). Axial transport of sediment from east to west is consistent with paleocurrents during the late Atoka. Comparison of observed strata characteristics within the parasequences with classic models is the basis for characterization of deposition for the Mansfield sand. The parasequences observed exhibit a coarsening upward increase in grain size, upward increase in sand to shale ratios, and relative thickness increase in sandstone beds (Figure 20). In addition, parasequence boundaries are marked by abrupt deepening, decrease in bed thickness, and change in lithology from sandstone below to shale above. These observations in parasequence characteristics are consistent with the model for a deltaic environment on a sandy, fluvial or wave-dominated shoreline (Figure 21). Following deposition of the Mansfield sand, there was an increase in accommodation exceeding the rate of sediment supply as sea level continued to rise into the late HST.

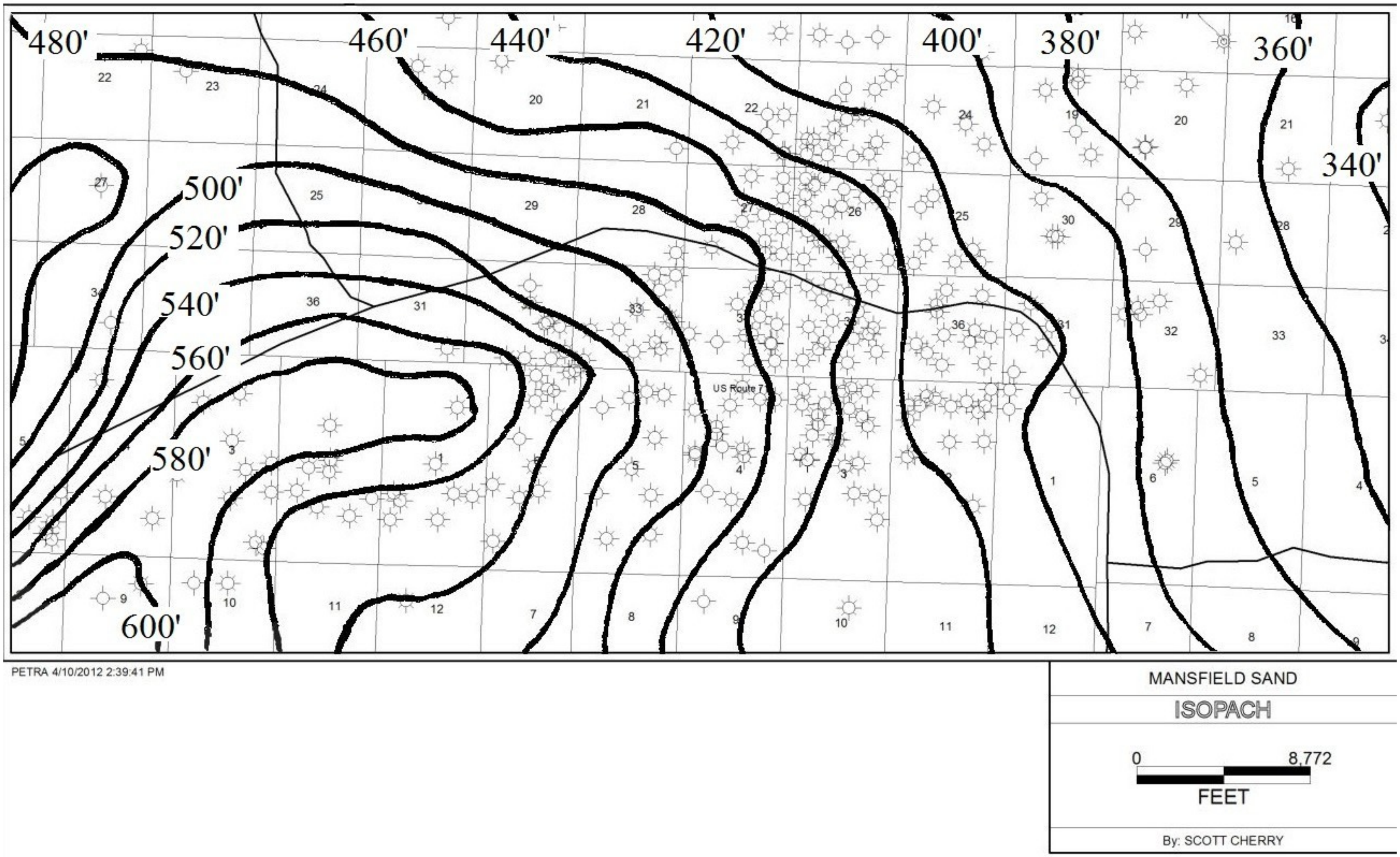


Figure 19. Isopach map for Mansfield sand.

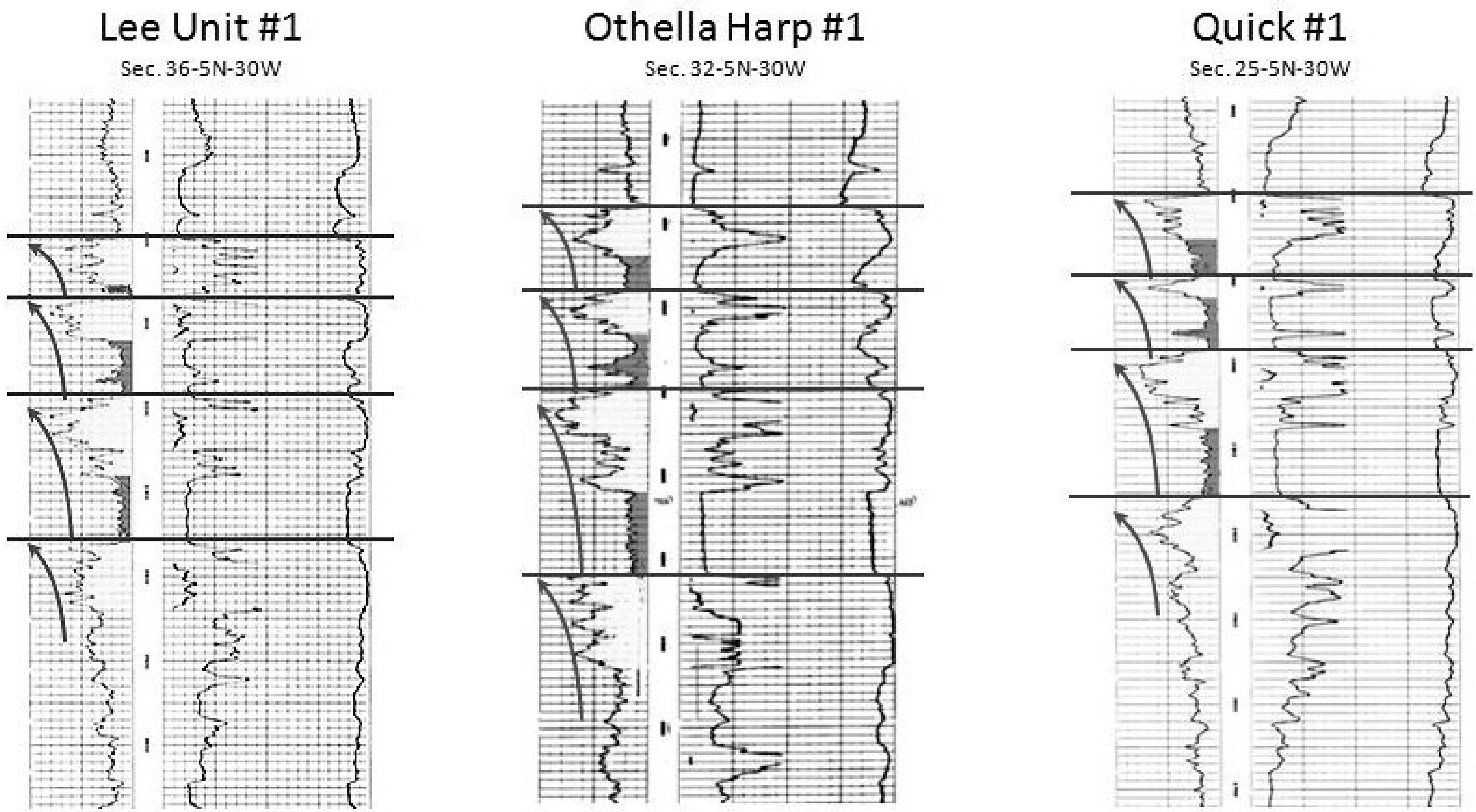


Figure 20. Well log signatures of parasequences exhibit coarsening upward trend in grain size, upward increase in sand to shale ratios, and relative thickness increase in sandstone beds

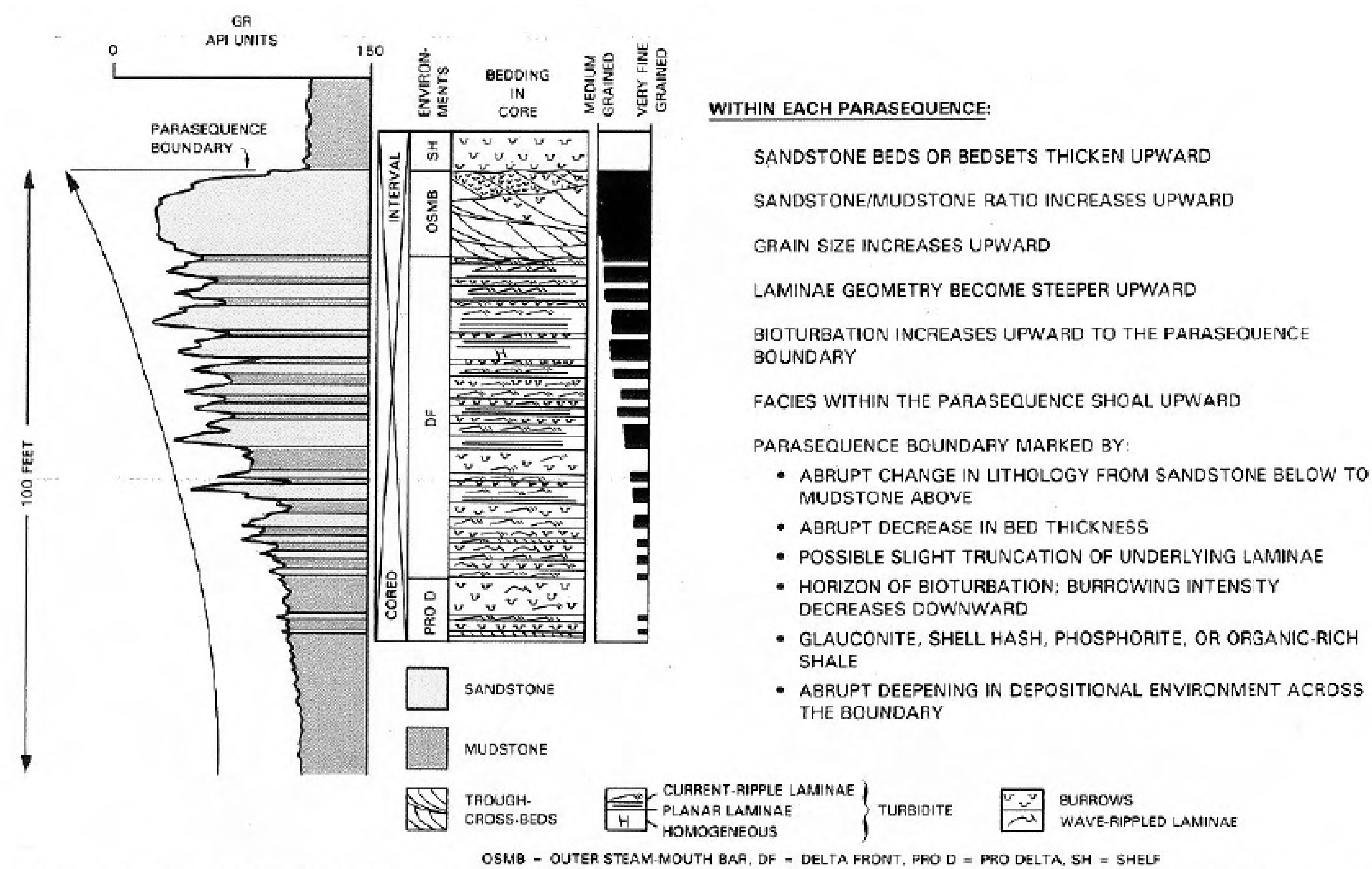


Figure 21. Stratal characteristics of parasequence interpreted to form in a deltaic environment on a sandy, fluvial- or wave-dominated shoreline (Figure 3B from Van Wagoner, 1990).

MINERALOGY OF THE MANSFIELD

Mineralogical analysis on drill cuttings obtained from Coop Ridge #1 was performed by a third party laboratory using X-ray diffraction, HCl solubility, HCl soluble iron content, and scanning electron microscopy (SEM). Samples were analyzed from measured depths of 1665, 1693 and 1760 feet, respectively, to quantify framework assemblages, accessory mineralogy, cementation, and porosity. These findings are listed in Appendix II.

The formation is fine grained quartzarenite sandstone, with quartz grains tightly cemented by secondary quartz overgrowth. Minor auxillary cementation by carbonate minerals is present. Intragranular porosity is low due to the extensive secondary quartz cementation. Feldspar and biotite and muscovite micas are minor accessory framework components. Minor amounts of carbonate minerals, on the order of 7%, are present in the form of calcite, dolomite, ankerite, and siderite. The formation contains 3-4% clay minerals in the form of chlorite and mixed layer illite/montmorillonite. The clay minerals are intermixed along pore walls and partially occlude pore space, and clay mineral migration and pore blockage results in a reduction in formation permeability. These are significant production considerations that must be managed through specific formulations of drilling fluids.

CONCLUSIONS

The Mansfield sand of the Atoka Formation is internally composed of seven distinct units of alternating sandstone and shale. The units are elongate, lobate bodies parallel to the axis of the Arkoma Basin. The Mansfield is interpreted as a fourth order sequence composed of four progradational parasequences. Wireline log signatures, parasequence stacking patterns, and formation geometry suggest deposition in a deltaic environment on a sandy, fluvial or wave dominated shoreline. Deposition occurred during a period of slow relative sea rise with terrigenous sediment influx occurring at a rate exceeding accommodation creation.

REFERENCES

Coleman Jr., J.L., 2000. Carboniferous Submarine Basin development of the Ouachita mountains of Arkansas and Oklahoma. In: A.H. Bouma and C. G. Stone, eds, Fine Grained turbidite systems, American Association of Petroleum Geologists Memoir 72/Society of Economic Paleontologists and Mineralogists Special Publication 68, p. 21-32.

Collier, A.J., 1907. The Arkansas Coal Field: United States Geological Survey Bulletin No. 326.

Galloway, W.E., 1989. Genetic stratigraphic sequences in basin analysis: architecture and genesis of flooding surface bounded depositional units. American Association of Petroleum Geologists Bulletin, 73, p. 125-142.

Houseknecht, D.W., 1986. Evolution from Passive Margin to Foreland Basin: The Atoka Formation of the Arkoma Basin, South-Central U.S.A., International Association of Sedimentologists, Special Publications 8, p. 327-345.

Houseknecht, D.W., and Kacena, J.A., 1983. Tectonic and sedimentary evolution of the Arkoma Basin in Tetonic-sedimentary evolution of the Arkoma Basin and guidebook to deltaic facies, Hartshorne Sandstone, Houseknecht, D.W. ed., Society of Economic Paleontologists and Mineralogists, Midcontinent Section, v. 1, p. 3-33.

McFarland, J.D., 2004. Stratigraphic Summary of Arkansas, Arkansas Geological Commission Information Circular 36, p. 15.

Mitchum, R.M., 1977. Seismic stratigraphy and global changes of sea level, part 11: glossary of terms used in seismic stratigraphy, in C.E. Payton, ed., Seismic stratigraphy applications to hydrocarbonexploration: American Association of Petroleum Geologists Memoir 26, p. 205–212.

Moyer, C., 1985. Subsurface stratigraphy of the Prarie Grove Member, Hale Formation (Morrowan), in Franklin and Logan Counties, Arkansas [Master's Thesis, Unpublished] University of Arkansas, Fayetteville, 82 p.

Posamentier, H.W., 1988. Fluvial deposition in a sequence stratigraphic framework. In: D.P. James & D.A. Leckie, eds., Sequences, Stratigraphy, Sedimentology: Surface and Subsurface. Memoir of the Canadian Society of Petroleum Geologists, Calgary, vol. 15, p. 582-583

Rider, M.H., and Kennedy, M., 2011. The Geological Interpretation of Well Logs (3rd Edition), Rider-French Consulting Ltd., p. 75-142.

Smith, C.D. Structure of the Fort Smith-Poteau gas field, Arkansas and Oklahoma: USGS Bulletin No. 541-B, 1913.

Sutherland, P.K., 1988. Late Mississippian and Pennsylvanian depositional history in the Arkoma basin area, Oklahoma and Arkansas: Geological Society of America Bulletin, v. 100, p. 1787-1802.

Taff, J.A., and Adams, G.I., 1900. Geology of the eastern Choctaw coal field, Indian Territory, United States Geological Survey Annual Report, vol. 21, part 2 p. 257-311.

Valek, E.J., 1999. Sequence Stratigraphy and Depositional Dynamics of the Atoka Formation (Pennsylvanian) Based on Surface Exposures in the Southern Exposures in the Southern Ozarks, Northwestern Arkansas, [Master's Thesis, Unpublished] University of Arkansas, Fayetteville, 104p.

Van Wagoner, J.C., R.M. Mitchum, K.M. Campion, and V.D. Rahmanian, 1990. Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: Concepts for high-resolution correlation of time and facies: American Association of Petroleum Geologists Methods in Exploration Series 7, 55 p.

Vail, P.R., R.M. Mitchum, Jr., R.G. Todd, J.M. Widmier, S. Thompson, III, J.B. Sangree, J.N. Bubb, and W.G. Hatlelid, 1977. Seismic stratigraphy and global changes in sea level, *in* C.E. Payton, ed., Seismic stratigraphy—applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, p. 49-205.

Wenger, R.J., 2002. Sequence Stratigraphy and Depositional Systems of the Tackett Sandstone, Middle Atoka Formation, Arkoma Basin, Arkansas, [Master's Thesis, Unpublished] University of Arkansas, Fayetteville, 69p.

Zachry, D.L., 1983. Sedimentologic Framework of the Atoka Formation, Arkoma Basin, Arkansas, in Tectonic-sedimentary evolution of the Arkoma Basin and guidebook to deltaic facies, Hartshorne Sandstone, Houseknecht (editor), Society of Economic Paleontologists and Mineralogists, Midcontinent Section, v. l, p. 34-52.

Zachry, D.L., and Sutherland, P.K., 1984. Stratigraphy and Depositional Framework of the Atoka Formation (Pennsylvanian) Arkoma Basin of Arkansas and Oklahoma, Oklahoma Geological Survey Bulletin 136, p. 9-17.

APPENDIX I: STRATIGRAPHIC CROSS SECTIONS

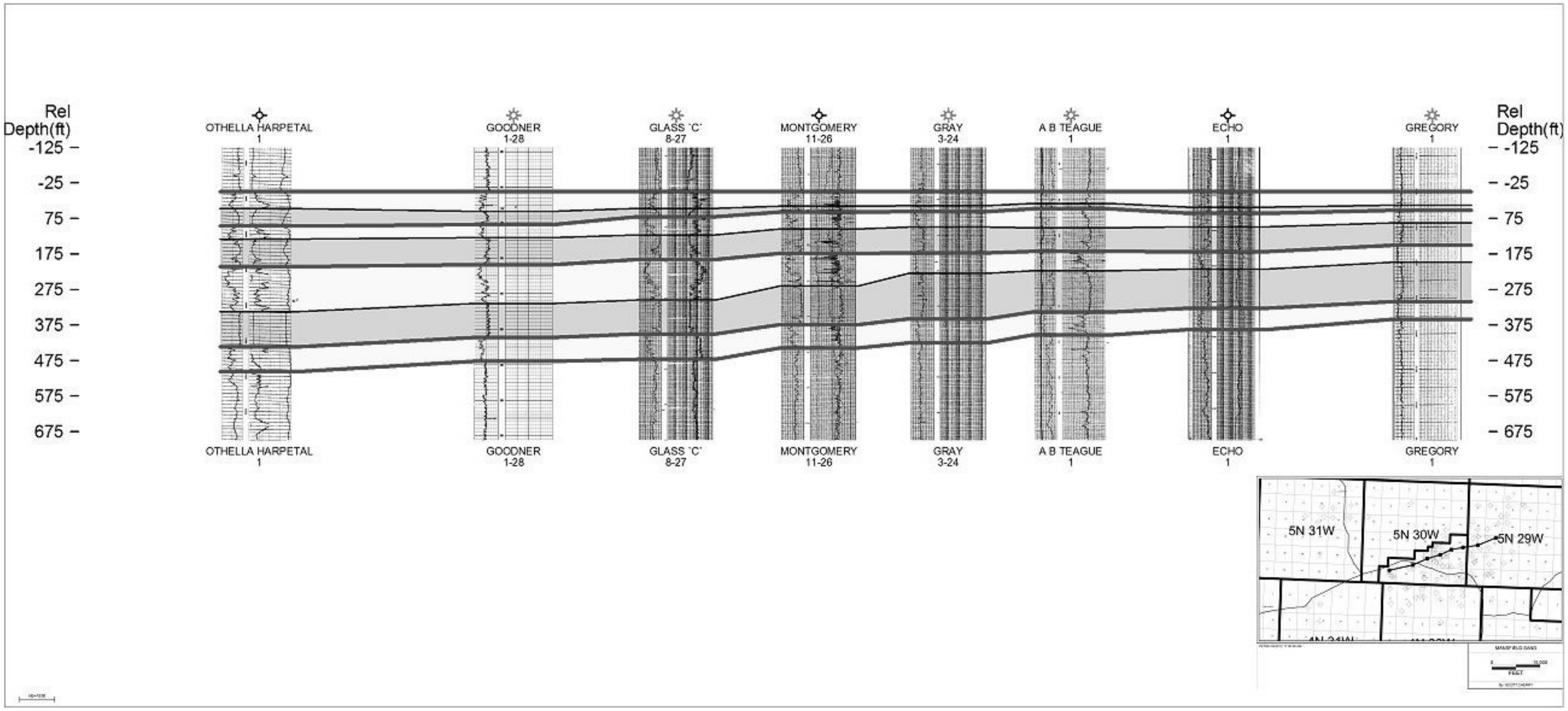


Figure 22. E-W stratigraphic cross-section of Mansfield sand in northern portion of the study area.

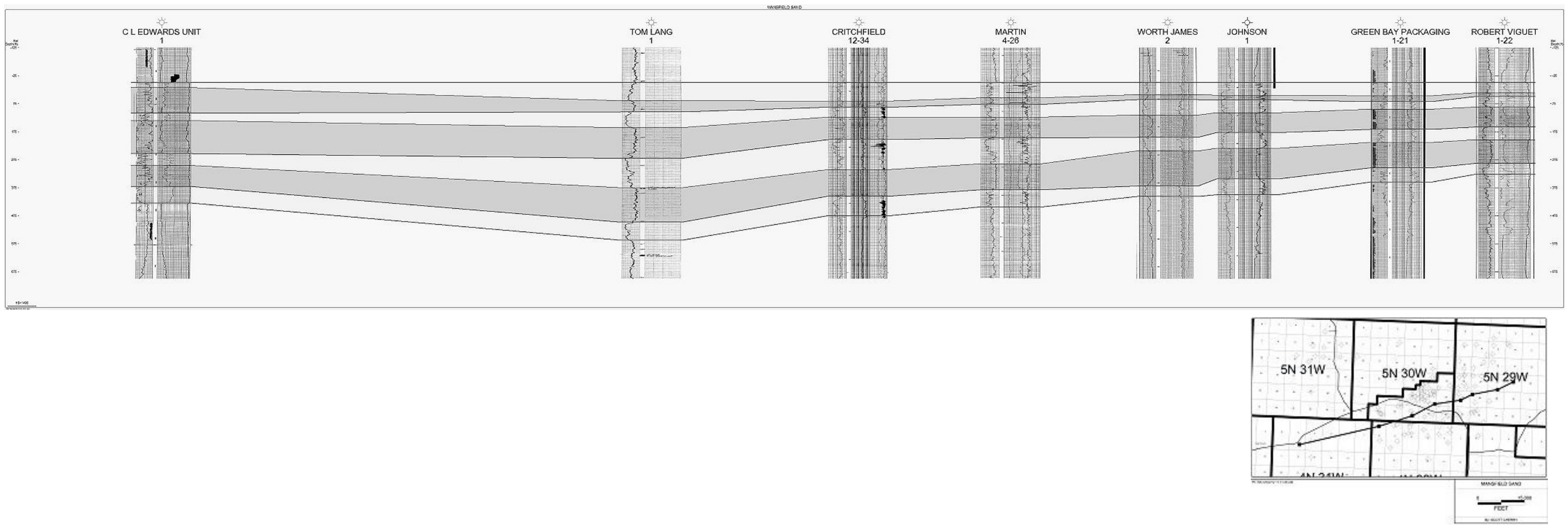


Figure 23. E-W stratigraphic cross-section of Mansfield sand through central portion of the study area, along the axis of the Hartford anticline.

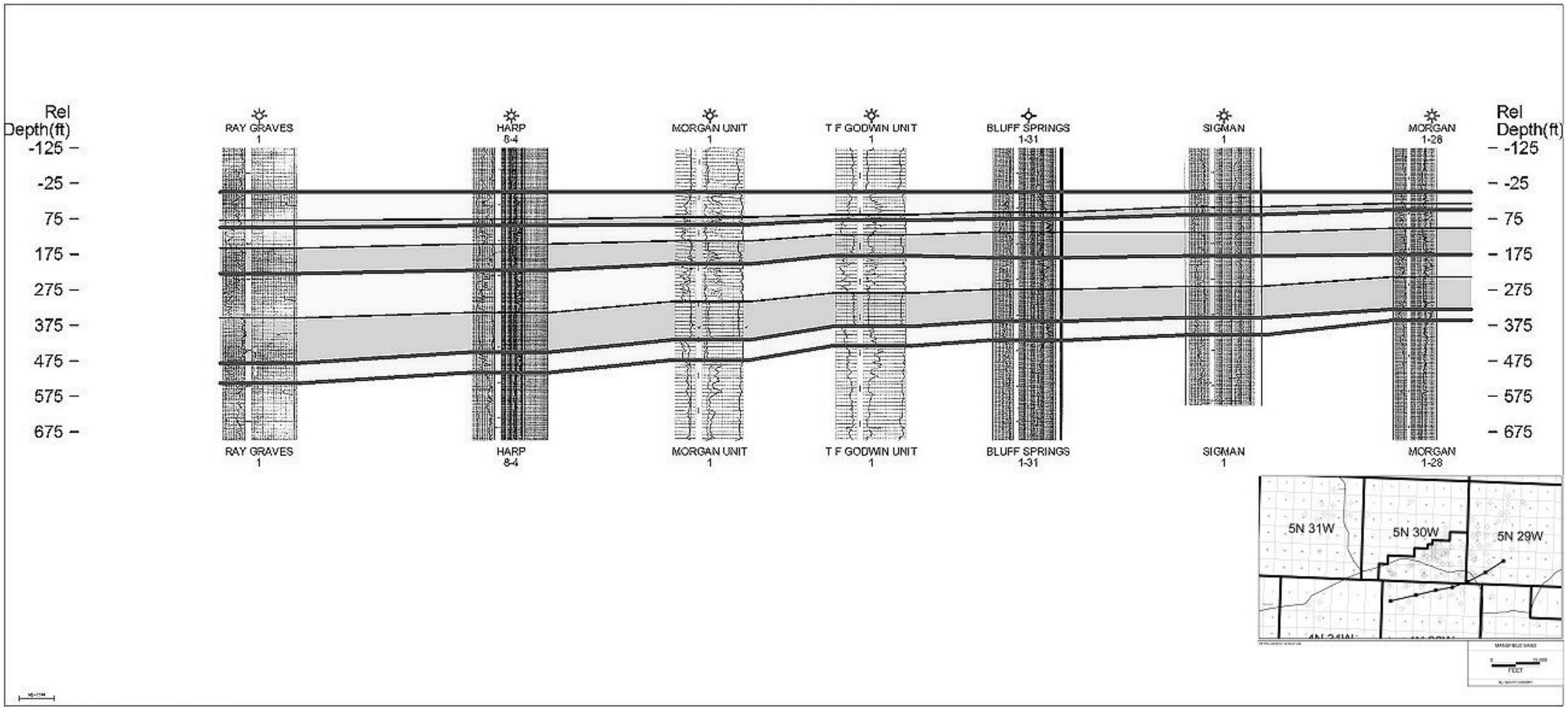


Figure 24. E-W stratigraphic cross-section of Mansfield sand in southern portion of the study area.

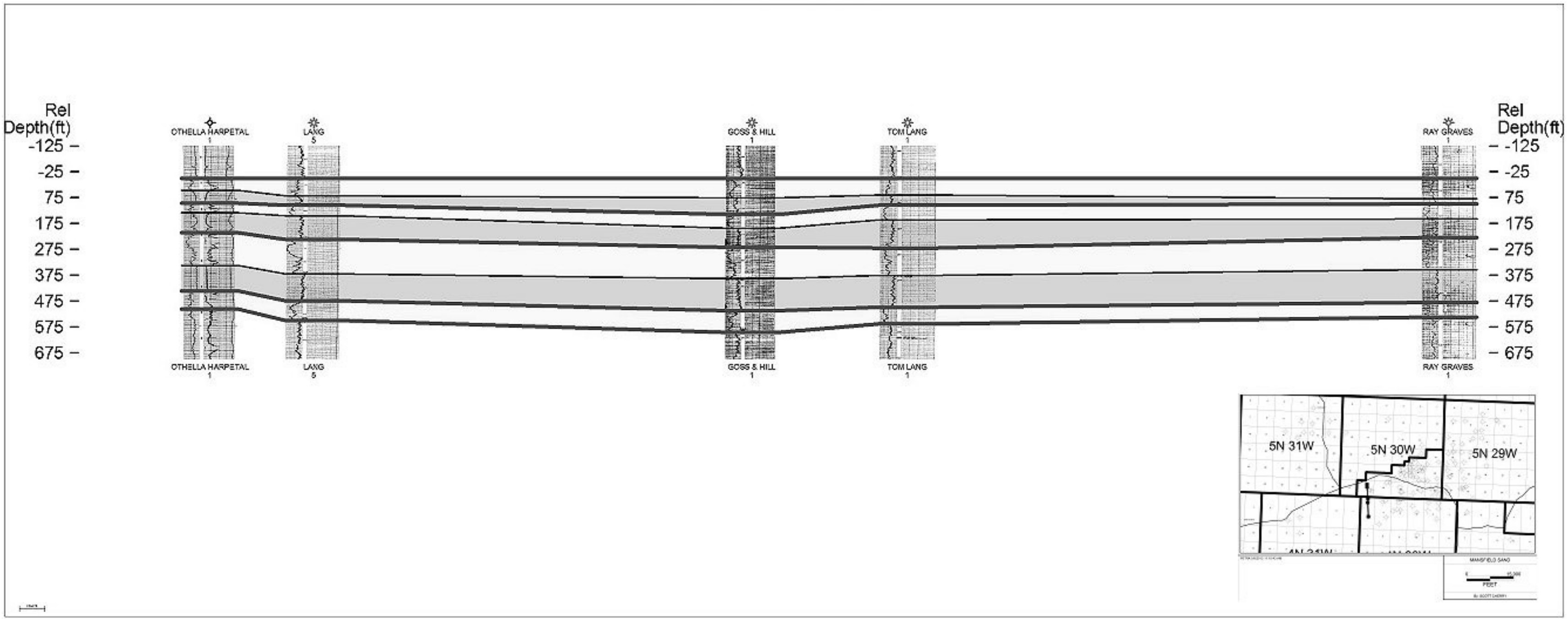


Figure 25. N-S stratigraphic cross-section of Mansfield sand in western central portion of the study area.

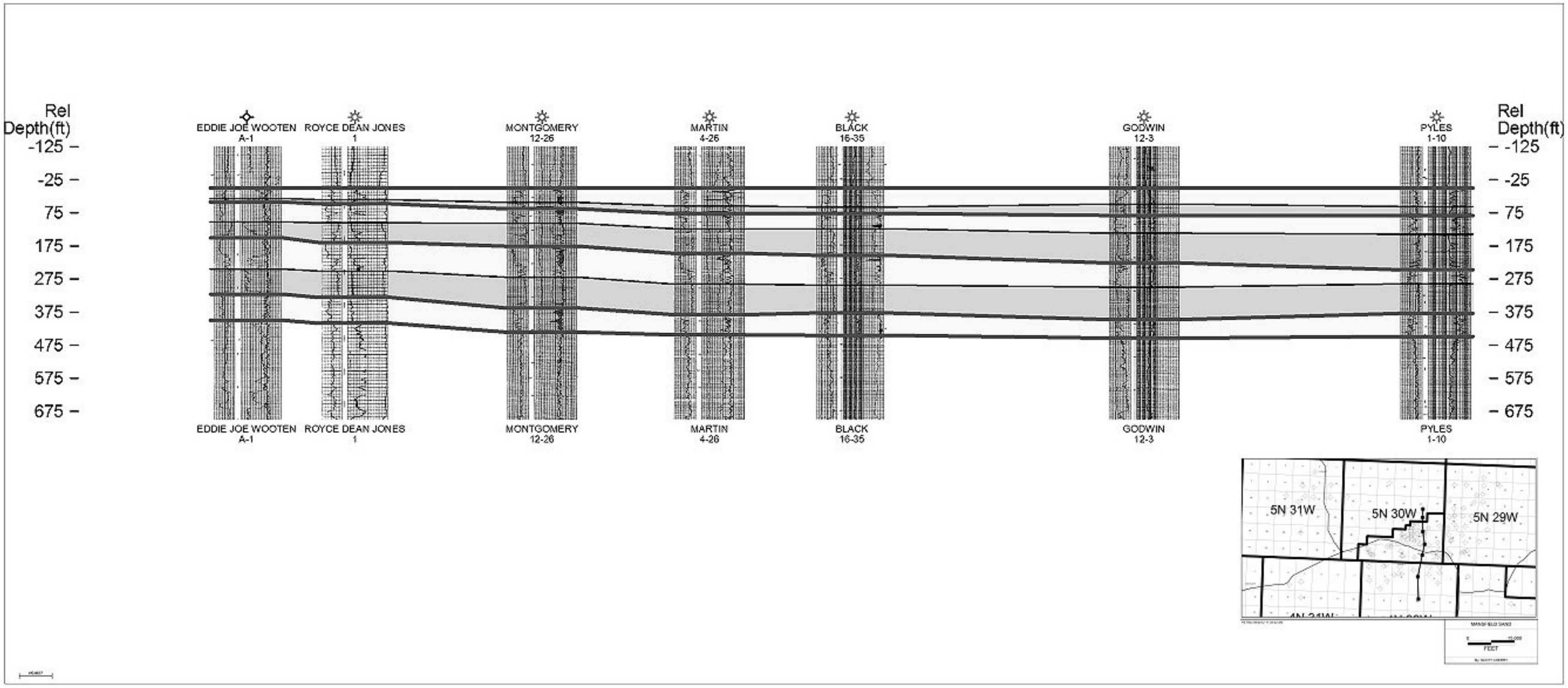


Figure 26. N-S stratigraphic cross-section of Mansfield sand in central portion of the study area.

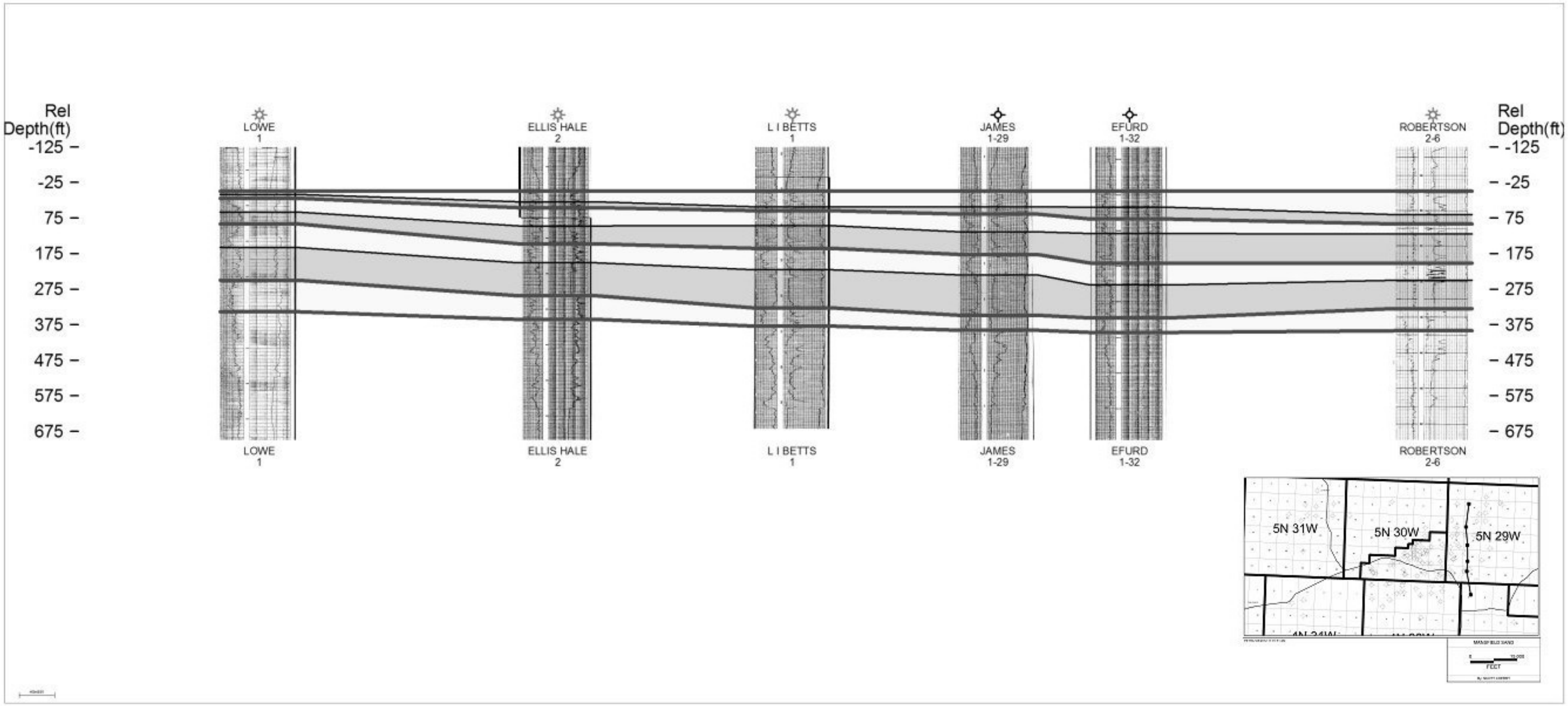


Figure 27. N-S stratigraphic cross-section of Mansfield sand in eastern portion of the study area.

APPENDIX II: MINERALOGICAL ANALYSIS

THE WESTERN COMPANY
Research Center
P.O. Box 186
Fort Worth, Texas, 76101

Table 1

Date: 11/5/87

X-RAY DIFFRACTION ANALYSIS NO. 7-2202

Operator:	M & P Exploration	Date Sampled:	Not Specified
Well:	Coup Ridge #1	Date Received:	10-22-87
Field:	Mansfield	Submitted By:	Jim Ford
Formation:	Not Specified	Source of Sample:	drill cuttings
Geologic Age:	Not Specified	Additional Information:	
County:	Not Specified		
State:	Arkansas		
Depth:	1665-1760 feet		
BHT:	Not Specified		

Sample Identification	Mineral Percentages																		
depth, ft	Quartz	Feldspar	Calcite	Dolomite	Siderite	Ankerite	Anhydrite	Pyrite	Barite	Kaolinite	Illite	Chlorite	Montmorillonite	Mixed Layer Illite/Mont.	Mixed Layer Chlorite/Mont.		Total		15% HCl Solubility (%)	15% HCl Soluble Iron Content (%)
1665	92	3	2		tr							2		1			100		5	0.97
1693	87	2	5		1	1						2		2			100		8	1.53
1760	94	2	tr	tr	tr							2		2			100		4	1.07

Comments:

Analyst George Polkowski
George Polkowski

Scanning Electron Microscopy Analysis #7-2202
Depth: 1665 ft
Date: November 5, 1987

I. Framework Constituents

The framework of this sandstone consists mainly of fine grained quartz sand.

II. Accessory Minerals

Feldspar is a minor accessory framework component.

III. Cementing Materials

Secondary quartz overgrowth cements the sand grains together. A minor amount of calcite acts as an auxiliary cement.

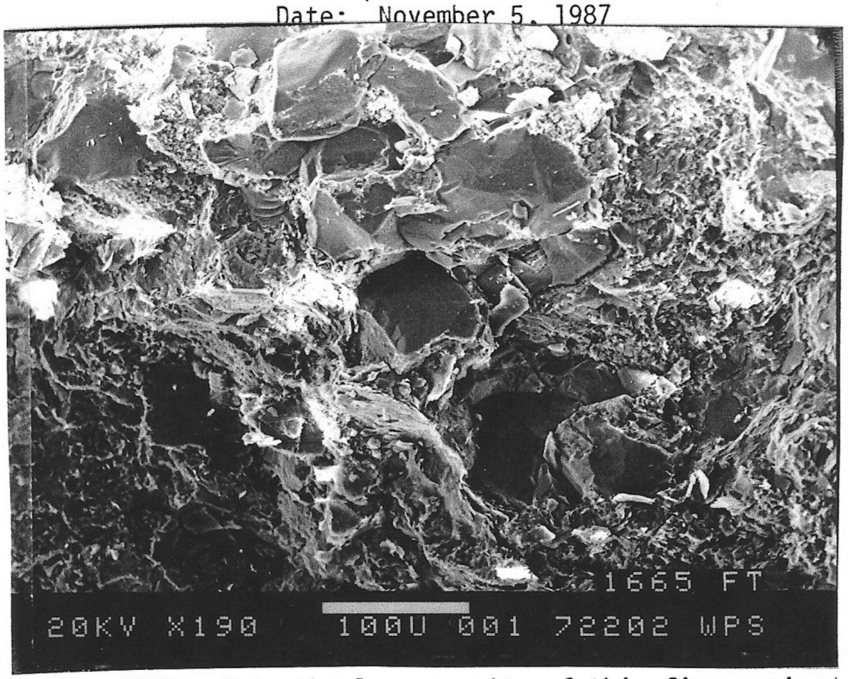
IV. Clay Mineral Content

Chlorite is the most abundant clay mineral. Illite-rich mixed layer illite/montmorillonite is also common. The two clays commonly occur intermixed with each other.

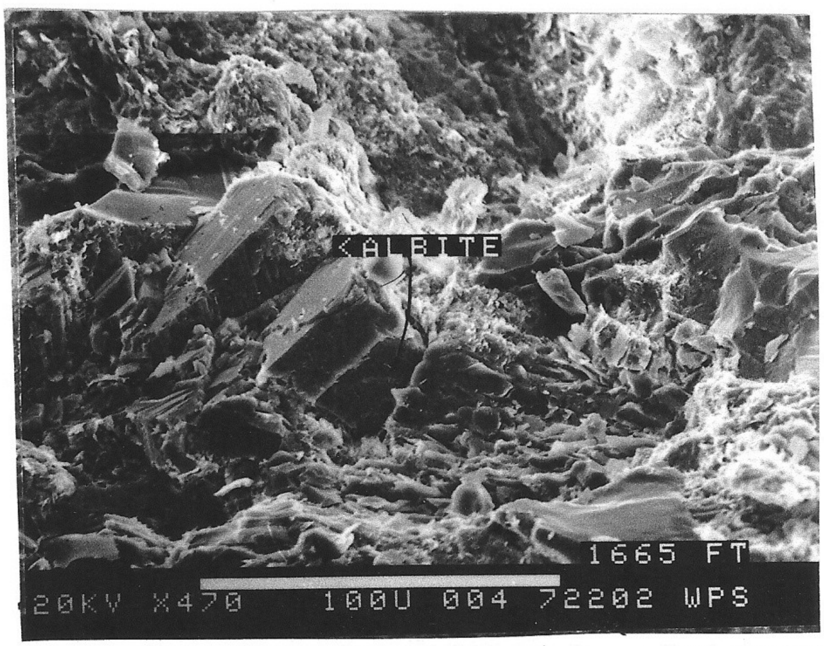
V. Porosity

Porosity is low due to extensive secondary quartz cementation. The remaining intergranular space is extremely occluded by clay minerals. Very minor secondary feldspar dissolution porosity is present. The formation at this depth should have very low permeability.

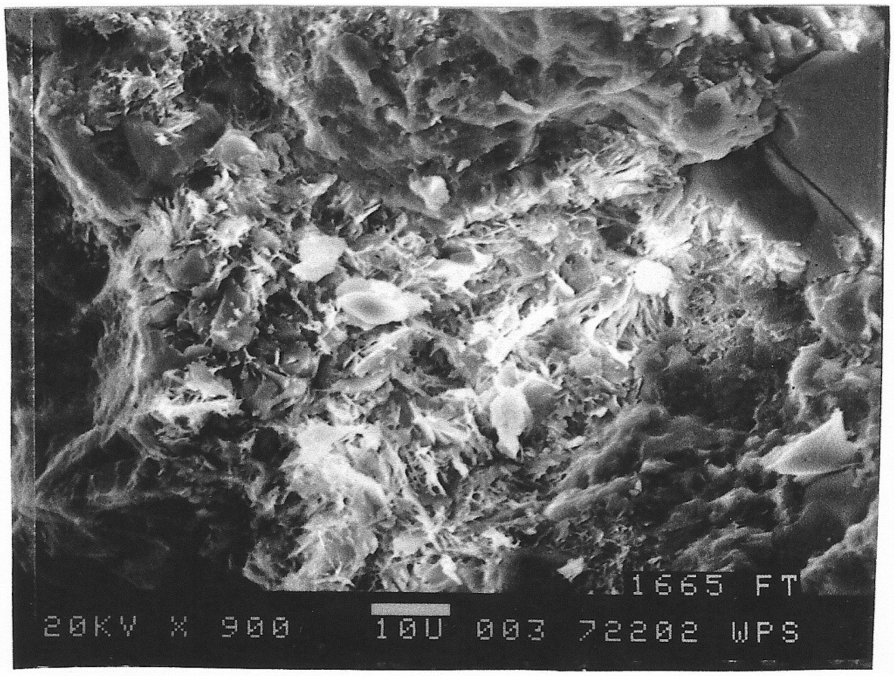
Scanning Electron Microscopy Analysis #7-2202
Depth: 1665 ft
Date: November 5, 1987



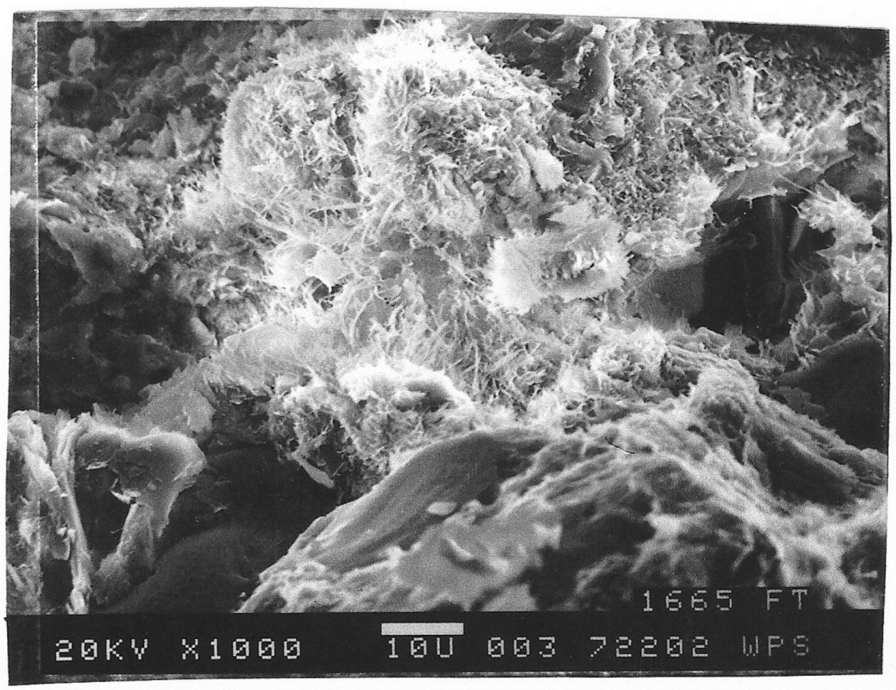
Photomicrograph #1 - 190X. Note the low porosity of this fine grained sandstone and the abundant clay minerals.



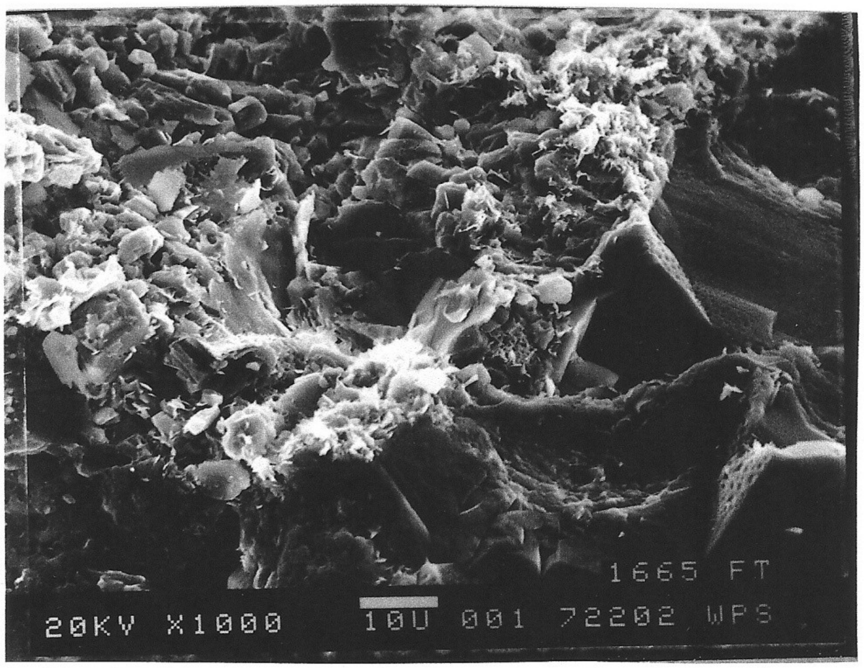
Photomicrograph #2 - 470X. Albite (Na - feldspar) is a minor component of this sandstone. Note the abundant clay.



Photomicrograph #3 - 900X. Chlorite and illite-rich mixed layer clay occur within the pores.



Photomicrograph #4 - 1000X. Another example of intermixed chlorite and illite-rich mixed layer clay.



Photomicrograph #5 - 1000X. Both chlorite and illite-rich mixed layer clay are present in the pores. Note also the crystal faces on the quartz sand grains in the right portion of the photo that are due to secondary quartz overgrowth.

Scanning Electron Microscopy Analysis #7-2202
Depth: 1693 feet
Date: November 5, 1987

I. Framework Constituents

The framework of this sandstone consists predominantly of fine grained quartz sand.

II. Accessory Minerals

Feldspar and muscovite and biotite micas are minor accessory framework components.

III. Cementing Materials

Secondary quartz overgrowth tightly cements the sand grains together. The carbonate minerals calcite, ankerite, and siderite act as minor auxiliary cements.

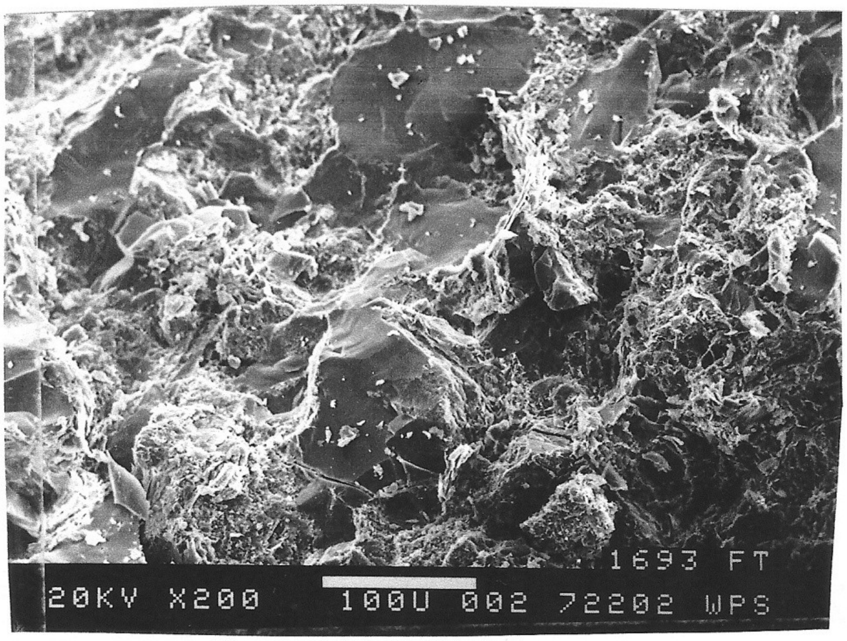
IV. Clay Mineral Content

Both chlorite and illite-rich mixed layer illite/montmorillonite appear to be equally abundant.

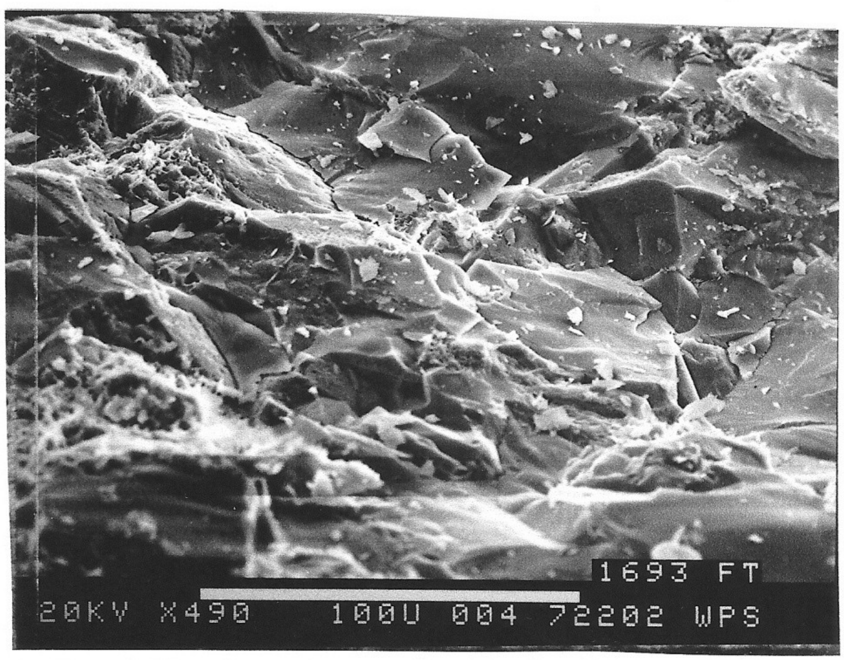
V. Porosity

Intergranular porosity appears to be low due to the extensive secondary quartz cementation. The pores are extremely occluded by clay minerals. Minor secondary porosity is present due to the dissolution of unstable feldspar grains.

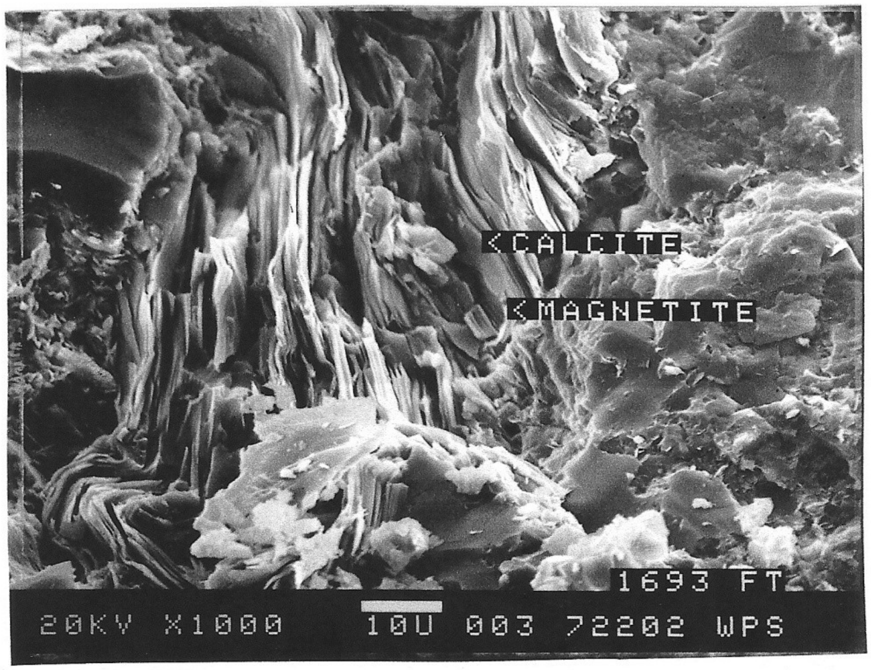
Scanning Electron Microscopy Analysis #7-2202
Depth: 1693 feet
Date: November 5, 1987



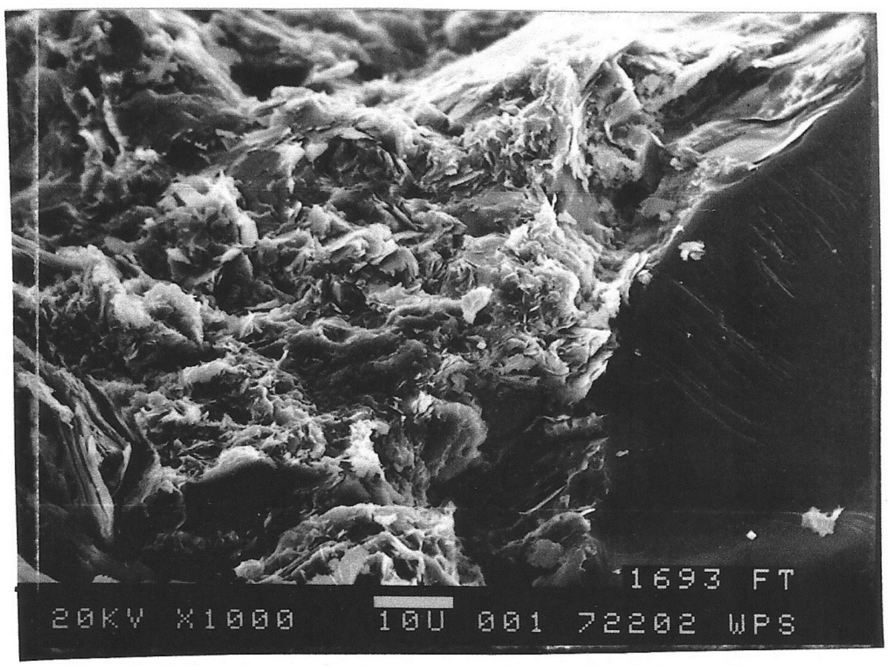
Photomicrograph #1 - 200X. The low porosity of this fine grained sandstone is evident. Note the abundant clay mineral deposits.



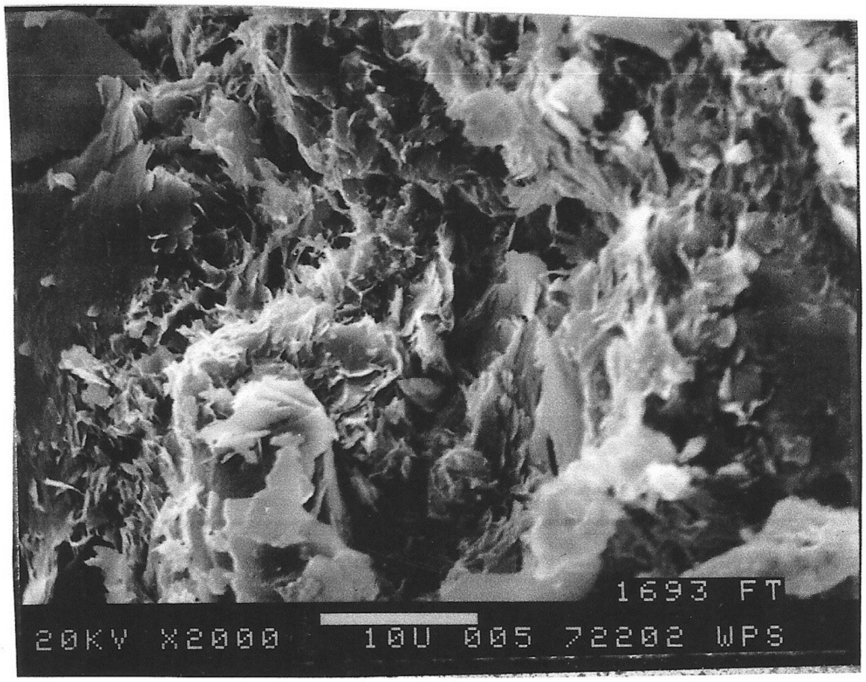
Photomicrograph #2 - 490X. Secondary quartz overgrowth has obliterated most of the original primary intergranular porosity.



Photomicrograph #3 - 1000X. A crushed biotite mica grain has small crystals of calcite and magnetite adjacent to it.



Photomicrograph #4 - 1000X. An equal mixture of chlorite and illite-rich mixed layer clay is common in the pores.



Photomicrograph #5 - 2000X. This is a close up view of intermixed chlorite and illite-rich mixed layer clay.

Scanning Electron Microscopy Analysis #7-2202
Depth: 1760 feet
Date: November 5, 1987

I. Framework Constituents

The framework of this sandstone consists predominantly of fine grained quartz sand.

II. Accessory Minerals

Feldspar and biotite and muscovite micas are minor accessory framework components.

III. Cementing Materials

Secondary quartz overgrowth tightly cements the sand grains together.

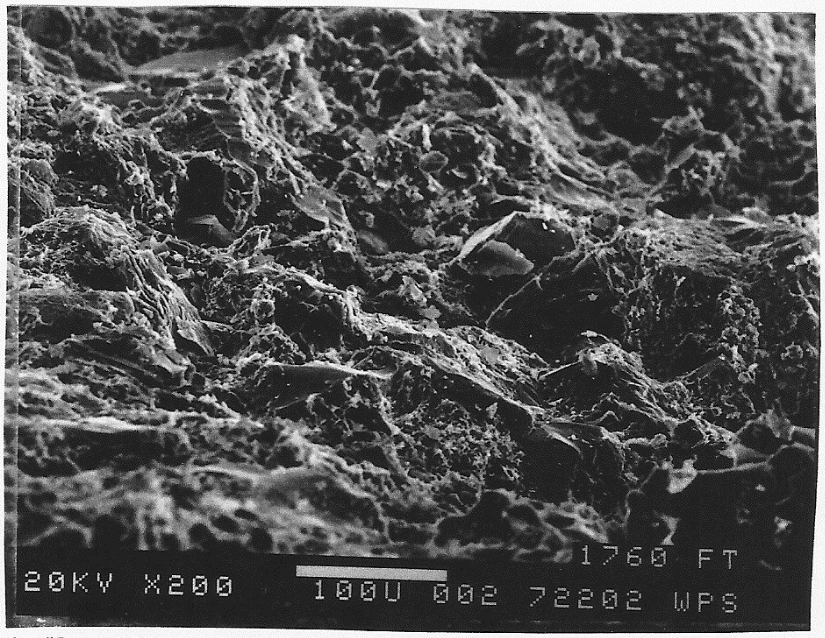
IV. Clay Mineral Content

Chlorite and mixed layer illite/montmorillonite appear to be equally abundant. Both are commonly seen intermixed along the pore walls.

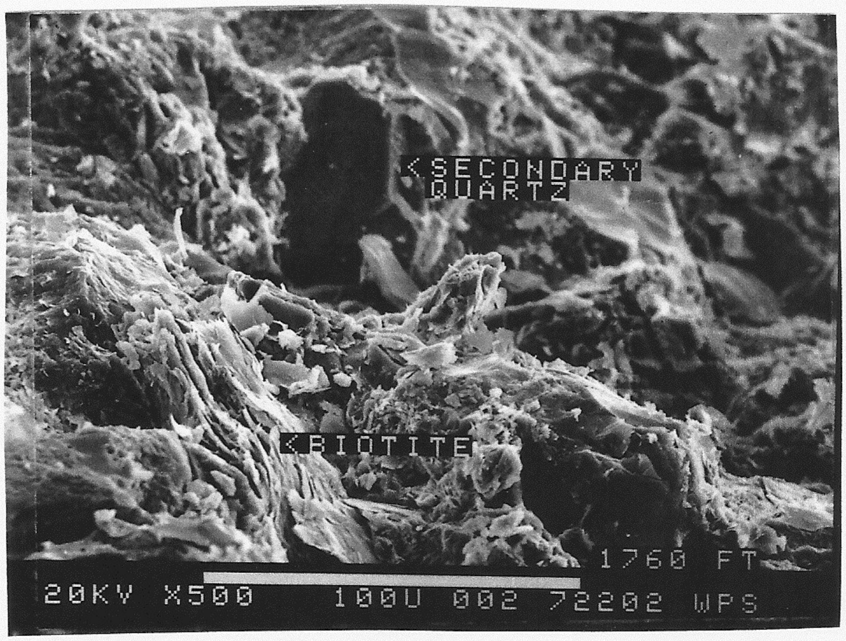
V. Porosity

Intergranular porosity is low due to the extensive amount of secondary quartz cement. The pores are partially occluded by clay minerals. Some minor feldspar dissolution porosity is also present.

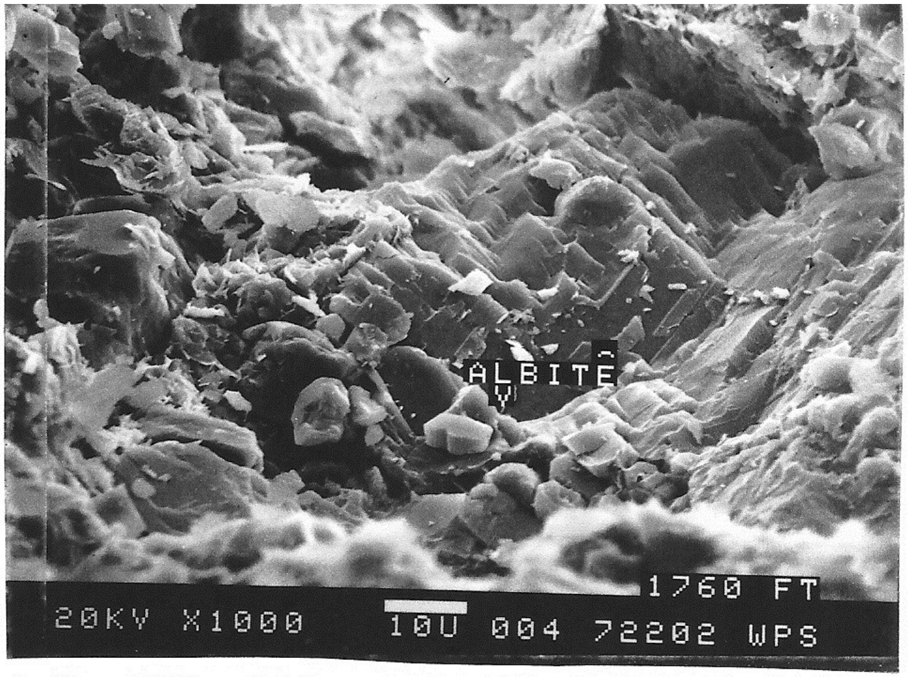
Scanning Electron Microscopy Analysis #7-2202
Depth: 1760 feet
Date: November 5, 1987



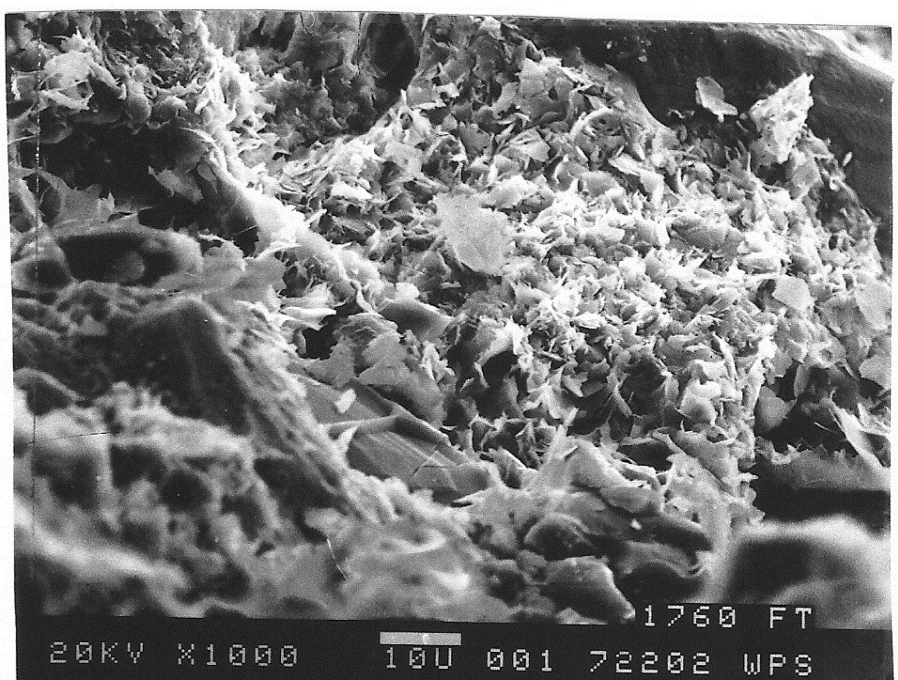
Photomicrograph #1 - 200X. This fine grained sandstone has little porosity. Note also the clay mineral deposits.



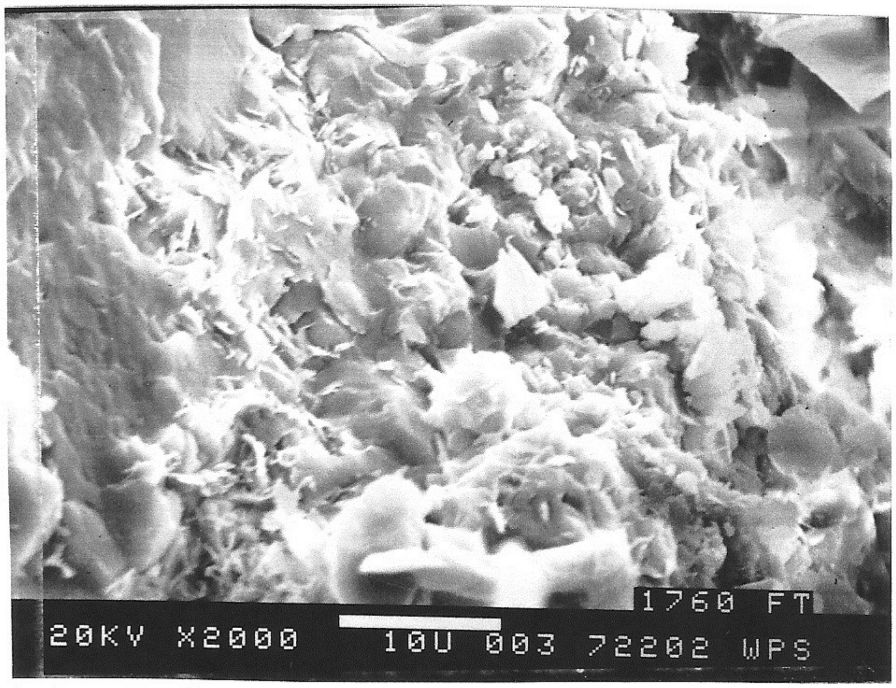
Photomicrograph #2 - 500X. Secondary quartz overgrowth cementation has resulted in the development of crystal faces on this sand grain. Note also the biotite mica.



Photomicrograph #3 - 1000X. Feldspar grains such as this one of albite (Na - feldspar) are minor components of the formation. Note also the small authigenic albite crystals.



Photomicrograph #4 - 1000X. The pores contain a mixture of chlorite and mixed layer clay.



Photomicrograph #5 - 2000X. This is a close up view of a pore wall. Both chlorite and mixed layer clay are present

Analyst George Polkowski
George Polkowski

APPENDIX III: LIST OF WELLS USED IN STUDY

Operator	Well Name	Well Label	API Number
STEPHENS PRDCTN CO	CHARLES G LOOPER	1-22	03131102260000
TXO PROD CORP	DISMUKES	1	03131102800000
TXO PROD CORP	JOHNNY CAKE	1	03131102820000
WHITMAR EXPL COMPANY	LEWIS	1-23	03131102880000
TXO PROD CORP	HICKEY	1	03131102920000
TXO PROD CORP	ECKLE	1	03131102990000
TXO PROD CORP	SANDERSON `A`	1	03131103240000
TXO PROD CORP	DILL `A`	1	03131103440000
TXO PROD CORP	NEISLER	1	03131103670000
BROWN B J	MANSFIELD LAKE	1	03131103770000
M & P EXPL CO INC	BARGER	1	03131103960000
M & P EXPL CO INC	BARGER	2	03131103980000
M & P EXPL CO INC	GODWIN S	1	03131104000000
M & P EXPL CO INC	COOP RIDGE	1	03131104280000
BROWN B J	CARLTON	1	03131104310000
TXO PROD CORP	HOLMES `G`	1	03131104340000
M & P EXPL CO INC	MARTIN ARDELL	1	03131104370000
MANSFIELD GAS INC	MANSFIELD	16	03131104510000
HANNA OIL & GAS CO	SMITH	1	03131104520000
M & P EXPL CO INC	BAGGETT DON	1-3	03131104530000
M & P EXPL CO INC	BROWN LARRY	1-3	03131104620000
M & P EXPL CO INC	BUGGY HILL	1	03131104650000
M & P EXPL CO INC	FEIMSTER	1	03131104680000
SONAT EXPL INC	GRIFFIN TRUST	1	03131105350000
SONAT EXPL INC	WITCHER	1	03131105400000
RAND OIL & GAS INC	HINES	1	03131105760000
SONAT EXPL INC	TEXAS JACK	1	03131106310000
SAGELY FLOYD O&G CO	WOOTEN E J	1-14	03131106990000
FREEDOM ENERGY	FROSCHAUER	1	03131107040000
FREEDOM ENERGY	GILKER	2	03131107140000
FREEDOM ENERGY	BUCCELLA	1	03131107150000
HANNA OIL & GAS CO	EFURD	2	03131107400000
HANNA OIL & GAS CO	WILSON	1	03131107450000
SEECO INCORPORATED	AINSWORTH	1-19	03131107510000
M & P EXPL CO INC	JOHNNY CAKE RANCH U	1	03131107560000
SHIELDS ENERGY INC	WHITSON	1-9	03131107570000
FREEDOM ENERGY	DUNN	1	03131107580000
SONAT EXPL INC	BASHAM	1	03131107670000
FREEDOM ENERGY CORP	HANCOX	1	03131107750000

SHIELDS ENERGY INC	DAYTON	2-8	03131107790000
HANNA OIL & GAS CO	SPRAYBERRY	1	03131108400000
SAGELY FLYD PROP LTD	AINSWORTH	2	03131108510000
FREEDOM ENERGY	DILL J A	1	03131108590000
M & P EXPL CO INC	LOKEY	1	03131108680000
M & P EXPL CO INC	GUSTAFSON	1	03131109490000
M & P EXPL CO INC	GUSTAFSON	2	03131109500000
FREEDOM ENERGY INC	BUCCELLA	2	03131110180000
FREEDOM ENERGY INC	BLACKJACK RIDGE	1	03131110270000
FREEDOM ENERGY INC	MCCAFFERTY	1	03131110580000
CHESAPEAKE OPERG INC	WOOTEN	1-14	03131110660000
CHESAPEAKE OPERG INC	HERMIE	1-15	03131110670000
FREEDOM ENERGY INC	GILKER	3	03131110710000
SEDNA ENERGY INC	CROSSROADS	1	03131110950000
SHIELDS OPER INC	CROSSROADS SOUTHWES	1-20	03131111210000
XTO ENERGY INC	HOLMES `G`	2-17	03131111730000
SEDNA ENERGY INC	WHEDBEE	1-9	03131111830000
M & P EXPL CO INC	EZELL	1	03131111890000
SHIELDS OPER INC	SUBSTATION	1-17	03131112090000
SEDNA ENERGY INC	DILL J A	2-15	03131112360000
XTO ENERGY INC	JONES R D	10-23	03131112780000
SEDNA ENERGY INC	WITCHER	2-18	03131112900000
XTO ENERGY INC	JOHNSON-BEDFORD	2-10	03131113220000
SEDNA ENERGY INC	ALLEN DOROTHY	1-22	03131113240000
CHOLLA PETROLEUM INC	HARTFORD	1	03131113590000
HIGHLAND OIL&GAS LLC	TURNER	1-13	03131113700000
XTO ENERGY INC	JONES R D	14-23	03131113780000
CHOLLA PETROLEUM INC	EZELL	1-1	03131113790000
HIGHLAND O&G CO	EZELL	1	03131113820000
CHOLLA PETROLEUM INC	JOHNNY CAKE RANCH	1-3	03131113920000
HIGHLAND OIL&GAS LLC	REANO	1	03131113950000
HIGHLAND OIL&GAS LLC	COTNER	1	03131113960000
HIGHLAND OIL&GAS LLC	HUMPHREYS	1	03131113970000
CHOLLA PETROLEUM INC	TRACE	1-5	03131113990000
HIGHLAND OIL&GAS LLC	BROWN TRUST	1	03131114030000
XTO ENERGY INC	JONES R D	15-23	03131114130000
SAGELY FLYD PROP LTD	YANCEY	1-21	03131114220000
SHAMROCK O&G CORP	W E CHUMLEY	1	03131300250000
SHAMROCK O&G CORP	T J BEAUDRY	1	03131300270000
SUNSET INT	FULGHAM	1	03131300460000
TEXAS O&G CORP	GLASS	C-1	03127100190000
HADSON PET USA INC	EXIE LITTLE	1-33	03127100200000

TEXAS O&G CORP	YOWELL	1	03127100210000
TXO PROD CORP	RUPE	1	03127100260000
TXO PROD CORP	COOP CREEK A	A-1	03127100300000
SOUTHWESTERN ENRG PR	ROBERTSON	1-6	03127100330000
QUAPAW O&G INC ETAL	WOMACK CECIL	1	03127100340000
DAVIS JOE D	GODWIN	1	03127100350000
DAVIS JOE D	LAWSON	1	03127100360000
QUAPAW O&G INC ETAL	GODWIN	1	03127100370000
M & P EXPL CO INC	GOODNER DONALD	1	03127100380000
M & P EXPL CO INC	BROWN	1-14	03127100410000
M & P EXPL CO INC	HENLEY WAYNE	1	03127100420000
M & P EXPL CO INC	GOODNER CHARLES	1	03127100430000
M & P EXPL CO INC	WOOD	1-15	03127100440000
M & P EXPL CO INC	GOODNER	3-33	03127100450000
PRUITT TL&SUP CO INC	LANG JIM	6	03127100460000
M & P EXPL CO INC	GOODNER DOROTHY	4	03127100470000
M & P EXPL CO INC	GODWIN T F	2	03127100480000
M & P EXPL CO INC	GOODNER NORMAN	5-33	03127100490000
M & P EXPL CO INC	SORRELS	1-25	03127100500000
M & P EXPL CO INC	GODWIN	3	03127100520000
M & P EXPL CO INC	SWAFFORD	1-34	03127100530000
M & P EXPL CO INC	MUSGROVE	1	03127100540000
PRUITT TL&SUP CO INC	NORRIS	2	03127100550000
M & P EXPL CO INC	SISK	1	03127100570000
REVERE CORP	QUICK	2	03127100580000
BROWN B J	WILLIAMS C A	1	03127100590000
M & P EXPL CO INC	GODWIN	4	03127100600000
M & P EXPL CO INC	GOSS LARRY	1	03127100610000
BROWN B J	ELMORE	1	03127100640000
M & P EXPL CO INC	JONES	1	03127100650000
PRUITT TOOL GAS DEPT	LANG	7	03127100680000
M & P EXPL CO INC	GODWIN	5	03127100690000
M & P EXPL CO INC	QUICK E E	1-X	03127100710000
M & P EXPL CO INC	WARE	1	03127100720000
M & P EXPL CO INC	HAWTHORNE	1	03127100730000
PRUITT TOOL GAS DEPT	MERGEN	5	03127100740000
M & P EXPL CO INC	GOSS LARRY	2	03127100750000
M & P EXPL CO INC	GODWIN	6	03127100760000
M & P EXPL CO INC	GODWIN	7	03127100770000
M & P EXPL CO INC	ROSS	1	03127100780000
SAGELY FLOYD O&G CO	MATHIS	2-16	03127100800000
AMOCO PROD CO	HARP UNIT	2	03127100820000
AMOCO PROD CO	LEE UNIT	2	03127100830000

DAVIS JOE D	JONES ROYCE DEAN	2	03127100840000
AMOCO PROD CO	CRITCHFIELD UNIT	2	03127100850000
AMOCO PROD CO	GODWIN UNIT	1	03127100860000
AMOCO PROD CO	BLACK UNIT #2	2	03127100870000
M & P EXPL CO INC	CHITWOOD	1	03127100880000
SEECO INCORPORATED	MAY	1-5	03127100890000
SEECO INCORPORATED	HENLEY	2-4	03127100900000
SONAT EXPL INC	GRAY	2	03127100910000
BUTTONWOOD PET INC	QUICK	3	03127100920000
SOUTHWESTERN ENRG PR	HENLEY	3-4	03127100930000
SAGELY FLOYD O&G CO	MARTIN ARDELL	1-26	03127100940000
AMOCO PROD CO	LEE	3-36	03127100950000
SOUTHWESTERN ENRG PR	HALL	1-5	03127100960000
M & P EXPL CO INC	GODWIN	8	03127100970000
DAVIS JOE D	GOODNER SHERRY	1	03127100980000
AMOCO PROD CO	CRITCHFIELD	3	03127100990000
AMOCO PROD CO	GODWIN A	1	03127101000000
AMOCO PROD CO	HARP UNIT `A`	1	03127101020000
SEECO INCORPORATED	MORGAN R	1-6	03127101050000
SOUTHWESTERN ENRG PR	DELTIC TIMBER	1-4	03127101060000
AMOCO PROD CO	BLACK	3-35	03127101070000
AMOCO PROD CO	CRITCHFIELD	5-34	03127101080000
FREEDOM ENERGY	QUICK	4	03127101090000
SEECO INCORPORATED	HOUSLEY	1-3	03127101100000
VASTAR RESOURCES INC	HARP	3-4	03127101110000
SEECO INCORPORATED	SPARLING	1-5	03127101120000
VASTAR RESOURCES INC	GODWIN	2-3	03127101130000
VASTAR RESOURCES INC	BLACK	4-35	03127101140000
VASTAR RESOURCES INC	PRAIRIE CREEK	1-2	03127101150000
VASTAR RESOURCES INC	PRAIRIE CREEK	2-2	03127101160000
VASTAR RESOURCES INC	LEE	4-36	03127101170000
VASTAR RESOURCES INC	PRAIRIE CREEK	3-2	03127101180000
VASTAR RESOURCES INC	BLACK	5-35	03127101190000
SAGELY FLYD PROP LTD	MONTGOMERY	1-26	03127101200000
CROSS TIMBERS OPR CO	QUICK	5-25	03127101210000
VASTAR RESOURCES INC	LEE	5-36	03127101220000
VASTAR RESOURCES INC	PRAIRIE CREEK	4-2	03127101230000
VASTAR RESOURCES INC	GODWIN	3-3	03127101240000
BP AMERICA PRODTN CO	BLACK	6-35	03127101250000
BP AMERICA PRODTN CO	GODWIN	4-3	03127101260000
DAVIS OPERATING CO	JONES ROYCE DEAN	3	03127101270000
SEECO INCORPORATED	WARE	1-3	03127101290000
MERIT ENERGY COMPANY	BLACK	7-35	03127101300000

MERIT ENERGY COMPANY	BLACK	8-35	03127101310000
MERIT ENERGY COMPANY	LEE	6-36	03127101320000
MERIT ENERGY COMPANY	CRITCHFIELD	6-34	03127101330000
MERIT ENERGY COMPANY	CRITCHFIELD	7-34	03127101340000
MERIT ENERGY COMPANY	BLACK	9-35	03127101350000
MERIT ENERGY COMPANY	BLACK	10-35	03127101360000
MERIT ENERGY COMPANY	BLACK	11-35	03127101370000
MERIT ENERGY COMPANY	BLACK	12-35	03127101380000
MERIT ENERGY COMPANY	BLACK	13-35	03127101390000
MERIT ENERGY COMPANY	CRITCHFIELD	8-34	03127101400000
MERIT ENERGY COMPANY	HARP	4-4	03127101410000
MERIT ENERGY COMPANY	GODWIN	5-3	03127101420000
MERIT ENERGY COMPANY	GODWIN	6-3	03127101430000
MERIT ENERGY COMPANY	LEE	7-36	03127101440000
MERIT ENERGY COMPANY	BLACK	14-35	03127101450000
MERIT ENERGY COMPANY	LEE	8-36	03127101460000
MERIT ENERGY COMPANY	CRITCHFIELD	9-34	03127101470000
MERIT ENERGY COMPANY	CRITCHFIELD	10-34	03127101480000
MERIT ENERGY COMPANY	HARP	5-4	03127101490000
MERIT ENERGY COMPANY	GODWIN	7-3	03127101500000
MERIT ENERGY COMPANY	BLACK	15-35	03127101510000
XTO ENERGY INC	MARTIN	2-26	03127101520000
XTO ENERGY INC	GLASS C	2-27	03127101530000
XTO ENERGY INC	GLASS `C`	3-27	03127101540000
XTO ENERGY INC	JONES R D	4-23	03127101590000
XTO ENERGY INC	JONES R D	5-23	03127101600000
XTO ENERGY INC	MONTGOMERY	2-26	03127101610000
MERIT ENERGY COMPANY	HARP	6-4	03127101620000
MERIT ENERGY COMPANY	GODWIN	8-3	03127101630000
MERIT ENERGY COMPANY	GODWIN	9-3	03127101640000
MERIT ENERGY COMPANY	GODWIN	10-3	03127101650000
MERIT ENERGY COMPANY	HARP	7-4	03127101660000
MERIT ENERGY COMPANY	CRITCHFIELD	11-34	03127101670000
XTO ENERGY INC	JONES R D	6-23	03127101680000
MERIT ENERGY COMPANY	BLACK	16-35	03127101690000
XTO ENERGY INC	GLASS `C`	4-27	03127101700000
XTO ENERGY INC	MARTIN	3-26	03127101710000
XTO ENERGY INC	GLASS `C`	5-27	03127101720000
MERIT ENERGY COMPANY	LEE	9-36	03127101730000
MERIT ENERGY COMPANY	LEE	10-36	03127101740000
SEDNA ENERGY INC	BLACKJACK RIDGE	2-22	03127101750000
XTO ENERGY INC	JONES R D	7-23	03127101770000
SEDNA ENERGY INC	BLACKJACK RIDGE	3-22	03127101780000

XTO ENERGY INC	MONTGOMERY	3-26	03127101800000
XTO ENERGY INC	GLASS C	6-27	03127101810000
XTO ENERGY INC	MONTGOMERY	4-26	03127101820000
XTO ENERGY INC	JONES R D	8-23	03127101830000
L & L ENERGY INC	ROBERTSON	2-6	03127101840000
MERIT ENERGY COMPANY	CRITCHFIELD	12-34	03127101850000
MERIT ENERGY COMPANY	LEE	11-36	03127101860000
XTO ENERGY INC	JONES R D	9-23	03127101870000
XTO ENERGY INC	JONES R D	11-23	03127101940000
XTO ENERGY INC	QUICK	6-25	03127101950000
MERIT ENERGY COMPANY	PRAIRIE CREEK	5-2	03127101960000
MERIT ENERGY COMPANY	PRAIRIE CREEK	6-2	03127101970000
MERIT ENERGY COMPANY	CRITCHFIELD	13-34	03127101980000
MERIT ENERGY COMPANY	LEE	12-36	03127101990000
XTO ENERGY INC	MONTGOMERY	5-26	03127102000000
MERIT ENERGY COMPANY	PRAIRIE CREEK	7-2	03127102010000
MERIT ENERGY COMPANY	HARP	8-4	03127102020000
XTO ENERGY INC	MARTIN	4-26	03127102030000
MERIT ENERGY COMPANY	GODWIN	12-3	03127102040000
XTO ENERGY INC	MONTGOMERY	6-26	03127102050000
XTO ENERGY INC	MONTGOMERY	7-26	03127102060000
XTO ENERGY INC	MONTGOMERY	8-26	03127102070000
XTO ENERGY INC	MONTGOMERY	9-26	03127102080000
XTO ENERGY INC	GLASS `C`	7-27	03127102100000
XTO ENERGY INC	MATHIS	3-26	03127102110000
XTO ENERGY INC	JONES R D	13-23	03127102120000
SAGELY FLYD PROP LTD	GOODNER	1-28	03127102130000
XTO ENERGY INC	MONTGOMERY	10-26	03127102140000
POTOCO LLC	MILTON	1-2	03127102150000
POTOCO LLC	PYLES	1-10	03127102160000
L & L ENERGY INC	REYNOLDS	1-5	03127102170000
XTO ENERGY INC	MONTGOMERY	11-26	03127102180000
XTO ENERGY INC	GLASS `C`	10-27	03127102190000
XTO ENERGY INC	GRAY	3-24	03127102200000
XTO ENERGY INC	GLASS `C`	11-27	03127102210000
XTO ENERGY INC	MONTGOMERY	12-26	03127102220000
XTO ENERGY INC	MONTGOMERY	13-26	03127102240000
SAGELY FLYD PROP LTD	GOSS LARRY	4-33	03127102250000
HIGHLAND OIL&GAS LLC	GOSS LARRY	3-33	03127120160000
HIGHLAND OIL&GAS LLC	JUDY	2	03127120170000
XTO ENERGY INC	GLASS `C`	8-27	03127120180000
XTO ENERGY INC	GLASS `C`	9-27	03127120190000
MIDWEST OIL PROD	BLACK UNIT	1	03127300000000

MIDWEST OIL PROD	CRITCHFIELD UNIT	1	03127300010000
MIDWEST OIL PROD	MORGAN UNIT	1	03127300020000
MIDWEST OIL PROD	LEE UNIT	1	03127300030000
MIDWEST OIL PROD	QUICK	1	03127300040000
WHEELER ROGER N	BLYTHE	1	03127300050000
SHAMROCK O&G CORP	OTHELLA HARPETAL	1	03127300060000
HAMON JAKE L	A B TEAGUE	1	03127300070000
GETTY OIL COMPANY	T F GODWIN UNIT	1	03127300090000
ROWAN DRILLING CO	LUTHER HENLEY UNIT	1	03127300100000
NICHOLS JNO EXPLO	GANN	1	03131000980000
DIAMOND SHMROCK CORP	JOHNSON-BEDFORD	1	03131100100000
DIAMOND SHMROCK CORP	FITZHUGH	1	03131100170000
MCCLAIN & BROWN	BARTON REUBEN	1	03131100180000
DIAMOND SHMROCK CORP	HERMAN STERLING	1	03131100290000
ADOBE OIL COMPANY	STEELE	1	03131100300000
ADOBE OIL & GAS CORP	PADDOCK	1-X	03131100350000
DIAMOND SHMROCK CORP	GILKER JAMES	2	03131100550000
DIAMOND SHMROCK CORP	C W GASAWAY	1	03131100620000
DIAMOND SHMROCK CORP	GANN M C	2	03131100650000
DIAMOND SHMROCK CORP	WHEDBEE J M	1	03131100700000
DIAMOND SHMROCK CORP	CENTRAL COAL & COKE	1	03131100710000
BROWN B J	HOYT GORDON	1	03131100740000
TEMPLETON OIL INC	C L EDWARDS UNIT	1	03131100860000
DIAMOND SHMROCK CORP	EDDIE JOE WOOTEN	A-1	03131101640000
HANNA OIL & GAS CO	JENNINGS	1	03131101660000
DIAMOND SHMROCK CORP	ROYCE DEAN JONES	1	03131101720000
MIDWEST OIL PROD	HARP	1	03127000010000
MIDWEST OIL PROD	ACME BRICK	1	03127000020000
LONE STAR GAS CO	C J WILLIAMS	1	03127000030000
WHEELER & RYAN	RAY GRAVES	1	03127000040000
WILSON PROD CO INC	E J HARP	1	03127100020000
PRUITT TL&SUP CO INC	MERGEN ROBERT	1-X	03127100060000
PRUITT TL&SUP CO INC	GOSS & HILL	1	03127100080000
PRUITT TL&SUP CO INC	TOM LANG	1	03127100100000
PRUITT TL&SUP CO INC	LANG	5	03127100110000
HADSON PET USA INC	BETHEL ESTATE	1-5	03127100150000
PRUITT TL&SUP CO INC	E J HARP	1	03127100160000
PRUITT TL&SUP CO INC	E J HARP	2	03127100180000
SHIELDS OPER INC	WORTH JAMES	3-31	03083109570000
SHIELDS OPER INC	BLUFF SPRINGS	1-31	03083110070000
SHIELDS OPER INC	PARKER RANCH	1-31	03083110090000
BISON EXPLORATION LP	TURNER UNIT	3-18	03083111160000
STEPHENS PRDCTN CO	SANDERSON	2-9	03083111370000

STEPHENS PRDCTN CO	ELLIS HALE	2	03083111380000
POTOCO LLC	MORGAN	1-28	03083111400000
HIGHLAND OIL&GAS LLC	POLINSKEY	1	03083111420000
HIGHLAND OIL&GAS LLC	POLINSKEY	2D	03083111830000
HIGHLAND O&G CO	GREGORY	1	03083111980000
POTOCO LLC	GREEN BAY PACKAGING	1-21	03083112140000
STEPHENS PRDCTN CO	LOWE	2	03083112210000
POTOCO LLC	HOLLEY	1-32	03083112280000
XTO ENERGY INC	COCHRAN	1-10	03083112410000
HIGHLAND OIL&GAS LLC	MORRIS	1-20	03083112720000
HIGHLAND OIL&GAS LLC	SANDERSON	1-19	03083112880000
TENNECO OIL CO	WORTH JAMES UNIT	1	03083300100000
TENNECO OIL CO	LOYD GLASS UNIT 1	1	03083300140000
TREBOL DRLG CO	L I BETTS	1	03083300180000
TRAHAN J C	W JAMES	1	03083300190000
HADSON PET USA INC	JAMES	1-29	03083100610000
HADSON PET USA INC	RATCLIFF	1-18	03083100930000
STEPHENS PRDCTN CO	ROBERT VIGUET	1-22	03083101230000
STEPHENS PRDCTN CO	ENGELKING	1-7	03083102350000
STEPHENS PRDCTN CO	LOWE	1	03083102520000
STEPHENS PRDCTN CO	SANDERSON	1-9	03083102930000
STEPHENS PRDCTN CO	COCHRAN	2-4	03083102980000
STEPHENS PRDCTN CO	HOPE	1-16	03083103030000
HANNA OIL & GAS CO	ECHO	1	03083103050000
LYSANDER RESOURCES	COCHRAN DAISY BIRD	1-10	03083103210000
STEPHENS PRDCTN CO	HALE ELLIS	1	03083103300000
BROWN B J	WORTH JAMES	2	03083103420000
CAN TEX ENERGY CORP	EFURD	1-32	03083103500000
M & P EXPL CO INC	SIGMAN	1	03083104060000
M & P EXPL CO INC	WORTH JAMES	3	03083104120000
SAGELY FLOYD O&G CO	JAMES WORTH	2-31	03083104180000
SAGELY FLOYD O&G CO	JAMES-GRAY	1-19	03083104350000
HANNA OIL & GAS CO	JOHNSON	1	03083105190000
BP AMERICA PRODTN CO	ECHO	2	03083105890000
CHESAPEAKE OPERG INC	WORTH JAMES	3-30	03083106650000

APPENDIX IV: DATA RELEASE

To Whom It May Concern,

As an authorized representative of M & P Exploration, Inc., I grant permission to Scott Cherry to use results and images of x-ray diffraction and scanning electron microscopy analyses of drill cuttings obtained from the Coop Ridge #1, API # 03 131 10428, in his graduate research conducted at the University of Arkansas.

Sincerely,

[redacted]

T. H. Musgrove
President
M & P Exploration, Inc.